TABLE OF CONTENTS

This subcourse will complete your study of electronic fundamentals. It will be necessary for you to have a good knowledge of basic electricity and electronics (MM0705, Part I) to fully understand the circuits taught herein. These circuits are widely used throughout all branches of the service in all fields of electronics.

This subcourse consists of nine lessons and an examination organized as follows:

Lesson 1	Frequency Modulation	2 hours
Lesson 2	Limiters and Discriminators	2 hours
Lesson 3	Special Purpose Oscillators	2 hours
Lesson 4	Multivibrators and Phantastrons	3 hours
Lesson 5	Sweep Generators	2 hours
Lesson 6	Transmission Lines and Waveguides	4 hours
Lesson 7	Antennas	3 hours
Lesson 8	High Frequency Oscillators and Pulse Modulators	3 hours
Lesson 9	Synchro and Servo Systems	3 hours
Examination		2 hours

READ THIS PAGE

GENERAL INFORMATION

This subcourse consists of one or more lessons and an examination. Each of the lessons is divided into two parts; the text and the lesson exercises. For one-lesson subcourses, the lesson exercises serve as the examination. A heading at the beginning of each lesson gives the title, the hours of credit, and the objectives of the lesson. The final examination consists of questions covering the entire subcourse.

If a change sheet is included, be sure to post the changes before starting the subcourse.

THE TEXT

All the text material required for this subcourse is provided in the packet. The text is the information you must study. Read this very carefully. You may keep the text; however, any unused answer cards and envelopes should be returned.

THE LESSON EXERCISES

Following the text of each lesson are the lesson exercises. After you have studied the text of each lesson, answer the lesson exercises. After you have answered all the questions, go back to the text and check your answers. Remember your answers should be based on what is in the text and not on your own experience or opinions. If there is a conflict, use the text in answering the question.

When you are satisfied with your answers, check them against the approved solution found in the back of the book. Restudy those areas where you have given an incorrect answer by checking the reference given after each answer.

THE EXAMINATION

After you have completed all the lessons and exercises, select the correct answer to all the examination questions. Carefully mark the correct answer on the TSC Form 59. Be sure that your Social Security number and subcourse number

printed on the TSC Form 59 are correct. Your final exam should be mailed in the envelope provided. The exam will be graded and you will be notified of the results. Your final grade for the subcourse will be the same as your examination grade.

ASSISTANCE

If you require clarification of anything in this subcourse write to us. Also, if you see any information in the text, which is incorrect or obsolete, your recommendations will be welcome. Be sure your recommendations are explained in detail, and, if possible, include a reference, which gives the correct information. Include your name and Social Security number.

LESSON 1. FREQUENCY MODULATION

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the principles of FM to include formation of sidebands, bandwidth, pre-emphasis, de-emphasis, the production of FM, and the reactance tube modulator.**
Lesson Credit Hours.....	**Two**

TEXT

1. INTRODUCTION.

a. In the armed services, a reliable radio communications system is of vital importance. The swiftly moving operations of modern armies require a degree of coordination made possible only by radio. Today, the two-way radio is standard equipment in almost all-military vehicles, and the walkie-talkie is a common sight in the infantry. Once, amplitude modulation (AM) communications was used universally. This system, however, has one great disadvantage; i.e., random noise and other interference can cripple communications beyond the control of the operator.

b. In the AM receiver, interference has the same effect on the radiofrequency (RF) signal as the intelligence being transmitted because they are of the same nature and inseparable. Engines, generators, and other electrical and mechanical systems generate noise that can disable the AM receiver. To avoid this difficulty different types of modulation, such as phase modulation (PM) or frequency modulation (f m), are used. When the amplitude of the RF signal is held constant, and the intelligence transmitted by varying some other characteristic of the RF signal, some of the disruptive effects of noise can be eliminated.

c. For this reason FM transmitters and receivers have not only become standard equipment in the Signal Corps, but their use in mobile equipment now exceeds that of AM transmitters and receivers. Thus, the widespread use of frequency modulation requires that we have a thorough understanding of its principles and the equipment it uses.

2. CARRIER CHARACTERISTICS.

a. The RF signal used to transmit intelligence from one point to another is called the carrier. It consists of an electromagnetic wave having amplitude, frequency, and phase. If the voltage variations of an RF signal are plotted with respect to time, the result is a waveform such as that shown in figure 1.

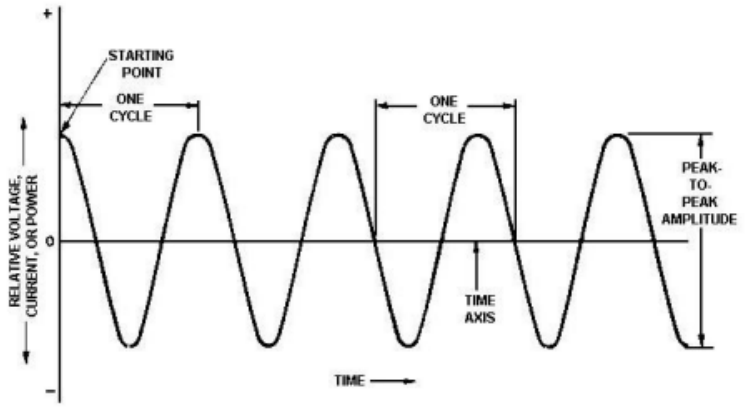


Figure 1. Graph of typical unmodulated carrier.

b. The unmodulated carrier is a sine wave that repeats itself in definite intervals of time. It swings first in the positive and then in the negative direction about the time axis and represents changes in the amplitude of the wave. This action is similar to that of alternating current in a wire, where the swings represent reversals in the direction of current flow. It must be remembered that the plus and minus signs used in figure 1 represent direction only and that the starting point of the curve is chosen arbitrarily.

c. Once a starting point is chosen, it represents the point from which time is measured. The starting point (fig 1) finds the curve at the top of its positive swing. The curve then swings through 0 to some maximum amplitude in the negative direction, returning through 0 to its original position. The changes in amplitude that take place in this interval of time are repeated without change as long as the carrier remains unmodulated. A full set of values occurring in any equal period of time, regardless of the starting point, constitutes one cycle of the carrier. The number of cycles that occur in 1 second is called the frequency of the wave.

3. MODULATING SIGNAL AMPLITUDE AND FREQUENCY DEVIATION.

a. In a frequency-modulated wave, the frequency varies instantaneously about the unmodulated carrier frequency in proportion to the amplitude of the modulating signal. When the modulating signal increases in amplitude the instantaneous frequency increases, and when the modulating signal decreases the frequency decreases.

b. A radiofrequency carrier and an audiofrequency signal are shown separately in A and B of figure 2. When these two waves are combined in the modulation process, the resultant signal is the FM wave in C of figure 2. As the amplitude of the audio signal increases in the positive direction, the modulated waves seem to bunch up. When the audio signal goes in the negative direction, the modulated waves appear to spread out. When the modulating signal is increased in amplitude, as in D, the changes in the spacing of the waves are proportionally greater, as in F (fig 2). Therefore, the amount of frequency deviation of the modulated wave is directly proportional to the amplitude of the modulating signal. When the audio voltage reaches its peak value in the positive direction, the frequency of the carrier is at its greatest value above the center value. The frequency of the carrier wave is reduced to its lowest value when the modulating voltage reaches its negative peak. Maximum frequency deviation, therefore, takes place at the peaks of the audio signal.

4. MODULATING SIGNAL FREQUENCY AND FREQUENCY DEVIATION. Figure 3 shows that each cycle of the modulating voltage (A) produces a corresponding variation in the frequency of the carrier wave (C). Two cycles of the audio wave produce two cycles of frequency change in the carrier. In D, the frequency of the modulating wave is increased so that, in the same time interval, the signal undergoes three complete cycles. Under this condition, the amount of frequency deviation remains the same because the amplitude of the modulating wave has not been changed. The result of increasing the frequency of the modulating signal can be seen by comparing C and F of figure 3. The audio signal is superimposed on the modulated carrier to demonstrate more clearly the relationship between the frequency of the modulating signal and the frequency changes in the carrier. This comparison indicates that the rate of frequency deviation is directly proportional to the frequency of the modulating signal.

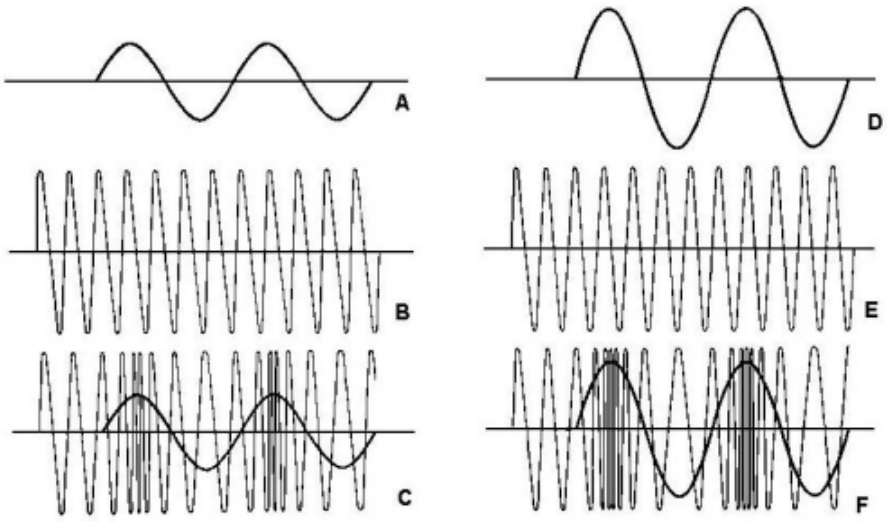


Figure 2. FM waves for modulating signals differing in amplitude.

5. CHARACTERISTICS OF FREQUENCY MODULATION.

a. The most important characteristics of a frequency-modulated wave are as follows: the amplitude of the modulated wave remains constant, the amount of frequency deviation of the modulated wave varies directly as the amplitude of the modulating signal, and the limits of frequency shift on either side of the carrier are known as the frequency deviation limits. In an FM system, the frequency of the modulating voltage determines the number of times per second that the frequency shifts between the deviation limits. The higher the frequency of the modulating signal, the greater number of times per second the frequency varies between the deviation limits set by the peak amplitude of the modulating signal. The ratio between the frequency deviation and the frequency of the modulating signal is called the modulation index. This is illustrated by the following equation:

$$\text{modulation index} = \frac{\text{frequency deviation}}{\text{frequency of modulating signal.}}$$

b. The modulation index in itself does not tell us anything. However, when it is applied to appropriate mathematical tables, we can determine the number of significant sidebands and the amplitude of each of these sidebands. In this way, we can tabulate information regarding the specific frequency spectrum formed at a particular instant.

6. PERCENTAGE OF FREQUENCY MODULATION. The percentage of modulation of an FM signal cannot be determined in the same manner as in an AM signal. Percentage of modulation in FM is defined as the percentage of maximum deviation incorporated in a transmitter for a particular type of service. For an FM transmitter with a maximum deviation of 75 kilohertzs (KHz) 100 percent modulation occurs when the transmitter deviates the full 75 KHz. If the deviation should fall to 37-½ KHz the transmitter would be modulated by only 50 percent. Therefore, with a maximum deviation of 75 KHz, if the transmitter deviation exceeds 75 KHz, it is said to be over modulated.

7. SIDEBANDS.

a. In an FM wave, the amplitude of the modulating signal determines the departure of the instantaneous frequency from the center, or the carrier frequency. The instantaneous frequency can be made to deviate as much as desired from the carrier frequency by changing the amplitude of the modulating signal. The sidebands generated by FM are not restricted to the sum and difference between the modulating frequency and the carrier as in AM.

b. As shown in figure 4, the FM wave consists of a carrier wave of frequency f_O and associated sideband frequencies of $f_O \pm fm$, $f_O \pm 2fm$, $f_O \pm 3fm$ (fm is the modulating frequency), etc. The number and amplitude of these sidebands are dependent upon the modulation index. With the centerline representing the carrier, the lines on each side of the centerline represent a particular component of the FM wave. The lines to the right of center represent the upper sideband frequency components, and those to the left represent the lower sideband components. The lengths of the lines represent the energy levels of the various components. The first pair of sidebands is the carrier frequency, plus and minus the modulating frequency. Also, a pair of sidebands will appear at each multiple of the modulating frequency. As a result, an FM signal occupies a greater bandwidth than does an AM signal.

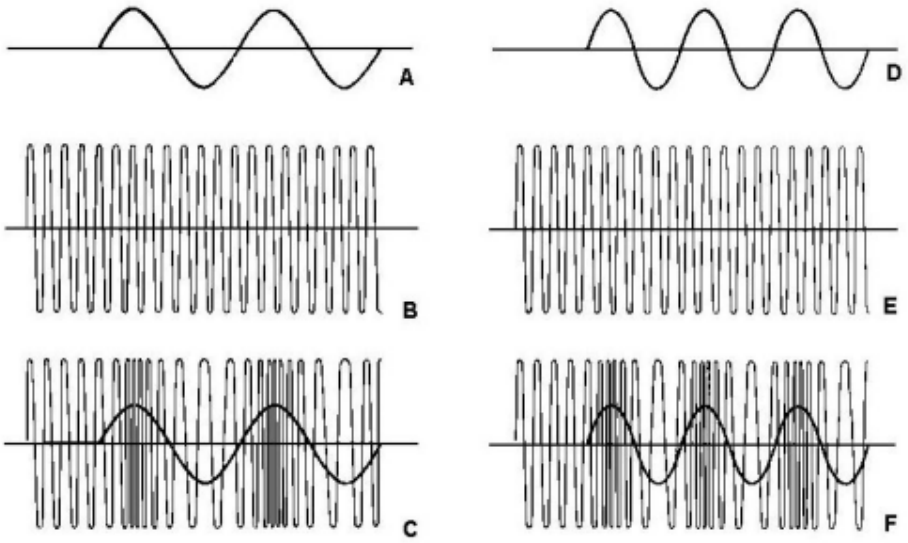


Figure 3. FM waves for modulating signals differing in frequency.

c. If a carrier of 1 megahertz (MHz) is frequency modulated by an audio signal of 10 KHz, several sidebands will be spaced equally on either side of the carrier frequency at 990 and 1,010, 980 and 1,020, 970 and 1,030, etc. The total number of sidebands of significant amplitude (more than 1 percent of the amplitude of the unmodulated carrier) depends on the modulation index. With a high modulation index more sidebands are of appreciable amplitude, but the bandwidth is not necessarily greater. As an example, with a frequency deviation (f d) of 75 KHz and a modulating frequency (f m) of 15 KHz, the modulation index (M) is 5.0. Referring to figure 5 we see that the number of significant sideband pairs is 8 and the bandwidth is 240 KHz. When the frequency deviation of 75 KHz is held constant and the modulating frequency is decreased to 5 KHz, the modulation index is increased to 15. The number of significant sideband pairs is now 19 (fig 5) but the bandwidth is only 190 KHz.

8. BANDWIDTH.

a. The bandwidth for frequency modulation is determined by the number of sidebands associated with the carrier. The maximum bandwidth of AM transmission is twice that of the maximum frequency present in the modulating wave. Since the bandwidth of an FM transmitter can exceed this by many times, the ratio of the bandwidth occupied to the absolute carrier frequency can be considerably larger. An FM wave is a very complex wave having an infinite number of sideband pairs instead of just one pair for each modulating frequency, as in amplitude modulation. Fortunately, however, only a limited number of sidebands contain sufficient energy to be significant.

b. The sideband components are spaced an amount equal to the modulation frequency. The product of the number of significant sideband components and the modulating frequency is equal to the bandwidth. For example, if the frequency deviation of the carrier (f d) is assumed to be 50 KHz and the modulating frequency (f m) is equal to 10 KHz, the modulation index will be 5 and there will be 8 significant sideband frequencies on each side of the carrier. Hence, the bandwidth is 8 x 10 KHz, on each side of the carrier for a total of 160 KHz.

c. FCC regulations limit the maximum deviation in FM transmission in order to prevent interference and to increase the number of channels. These maximum deviations are ± 75 KHz for commercial broadcast FM and ± 30 KHz, ± 15 KHz, ± 6 KHz, etc., for communication channels, depending upon the use or service of the particular band.

d. Although the FCC regulation limits the carrier shift to ± 75 KHz for commercial broadcast, some significant sidebands may extend beyond this frequency. A guard band of 25 KHz, on each side of the allowable frequency swing of ± 75 KHz, is established to include most of the significant sidebands beyond the established limits. Thus, each commercial FM station is allocated a 200 KHz channel.

9. ENERGY DISTRIBUTION.

a. The FM wave consists of a center or carrier frequency and a number of sideband pairs that, for a given audiofrequency and amplitude, are constant. The resultant wave is the algebraic sum of the components which form it. When the transmitted signal is unmodulated there is a constant amount of power in the carrier signal. When the modulation is applied, power is distributed between the carrier and the sidebands. This, therefore, reduces the amplitude of the carrier or center frequency component.

b. The carrier frequency, or center frequency component, changes in amplitude as modulation is applied. Since no information is contained in the FM carrier, reducing its amplitude increases the efficiency of operation in terms of usable power. For some values of the modulation index and modulating frequency, carrier amplitude falls to zero and all the power is contained in the sidebands.

c. In figure 6, with a frequency deviation of 30 KHz and a modulating frequency of 6 KHz, the center frequency component is reduced to less than 20 percent of the unmodulated amplitude. If the modulating frequency is reduced to 2 KHz, with the same frequency deviation of 30 KHz (fig 7), the center frequency component is reduced to only 1.4 percent of its unmodulated value.

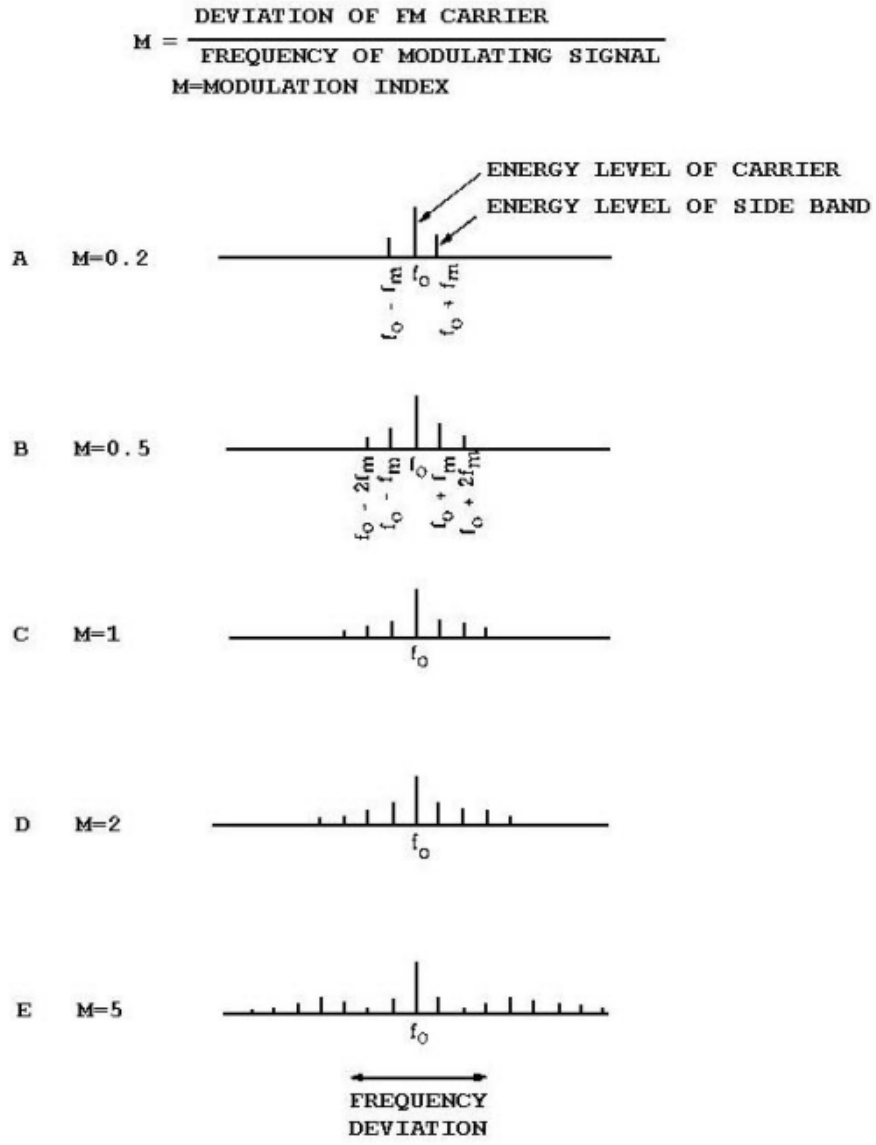


Figure 4. Frequency and energy distribution for 5 values of modulation index of an FM wave.

Modulation index $M = f_d / f_m$	Number of effective side-band pairs	Effective bandwidth
.5	2	$4f_m$
1	3	$6f_m$
2	4	$8f_m$
3	6	$12f_m$
4	7	$14f_m$
5	8	$16f_m$
6	9	$18f_m$
7	11	$22f_m$
8	12	$24f_m$
9	13	$26f_m$
10	14	$28f_m$
11	15	$30f_m$
12	16	$32f_m$
13	17	$34f_m$
14	18	$36f_m$
15	19	$38f_m$
16	20	$40f_m$
17	21	$42f_m$
18	23	$46f_m$
19	24	$48f_m$
20	25	$50f_m$
21	26	$52f_m$
22	27	$54f_m$
23	28	$56f_m$
24	29	$58f_m$
25	30	$60f_m$

Figure 5. Effective bandwidth for modulation index.

d. For the 6 KHz modulating frequency (fig 6) with a modulation index of 5, the total bandwidth is 96 KHz; with a 2 KHz modulating frequency and a modulating index of 15, the total bandwidth occupied is 76 KHz.

10. PRE-EMPHASIS AND DE-EMPHASIS.

a. Pre-emphasis.

(1) Pre-emphasis is the process whereby the higher audio frequencies are over-amplified in the modulating stage of a FM transmitter to improve the signal to noise ratio of the transmitted signal.

(2) Since the high frequency components of voice and music have a smaller amplitude than the low frequency components additional amplification of the high frequency components is possible without exceeding the maximum deviation limits set by the FCC. Therefore, by employing this process all signals will be large in relation to the inherent noise of the transmitting system.

(3) The pre-emphasis characteristics can be seen by plotting the audio input frequency and the modulated output amplitude on a graph (fig 8). The audio spectrum frequency is plotted horizontally and the output (in decibels) is vertically noted. This graph indicates that the output remains relatively constant from 50 to approximately 500 Hz and then rises abruptly to a peak of 15,000 Hz.

b. De-emphasis. At the receiver, the reverse characteristics of pre-emphasis are used so that the natural balance between high and low frequencies in speech and music is not upset. The characteristics of pre-emphasis and de-emphasis are normally achieved by simple RC networks, each having a time constant of 75 microseconds. (See figure 9.)

11. REACTANCE TUBE MODULATOR.

a. General.

(1) The purpose of the reactance tube modulator, in an FM transmitter system, is to frequency modulate the output of an oscillator in accordance with an audio signal. The modulator accomplishes this by changing the amplitude variations of the audio signal into a varying reactance that is injected into the tank circuit of the oscillator. This injected reactance then changes the output frequency of the oscillator.

(2) The reactance tube is an electron tube whose reactance varies with the modulating signal. This varying reactance causes the frequency of the oscillator stage to change accordingly.

(3) In figure 10, the reactance tube is connected in parallel with the oscillator tank. The tube functions like a capacitor whose capacitance is varied in accordance with the audio signal. Therefore, the output frequency of the oscillator is varied, and the resulting FM signal is passed through a frequency doubler to increase the carrier frequency and the deviation frequency. The final signal is then fed through a power amplifier to the antenna for radiation into space. The transmitter is kept within the assigned frequency limits by comparing the transmitter output with that of a standard crystal-controlled oscillator. If the limits are exceeded, a suitable correcting voltage, produced by a frequency converter and a discriminator stage, is fed to the reactance tube for correction.

(4) The theory of operation of a reactance tube circuit may be further explained by referring to figure 11. The reactance tube (V 1) is effectively in shunt with the oscillator tank (LC) and the phase-shift circuit (R 1 C 1). The capacitive reactance of the capacitor (C 1) is large compared to the resistance of resistor (R 1). Therefore, the RF signal applied to the grid of V 1 will produce a current (i p) which leads the RF voltage (e p) supplied by the tank by approximately 90°. The reactance tube now appears to the oscillator tank as a capacitor since the RF current produced by the tube leads the RF voltage across the tank and tube by 90°. Capacitor C c has no effect on the RF voltage and current. It keeps the DC plate voltage from the oscillator tank.

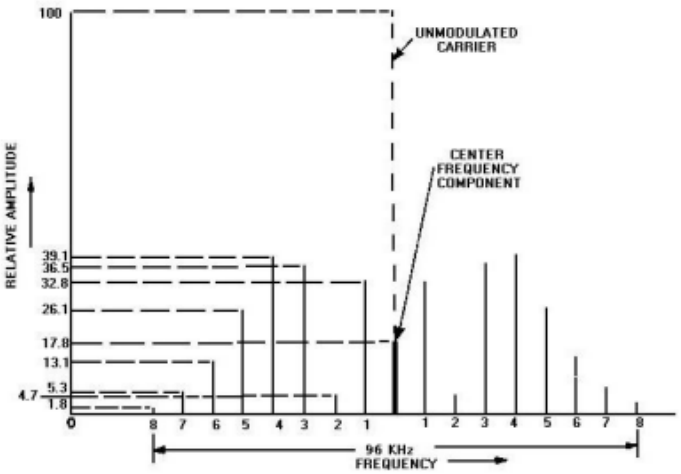


Figure 6. Frequency spectrum of FM wave.

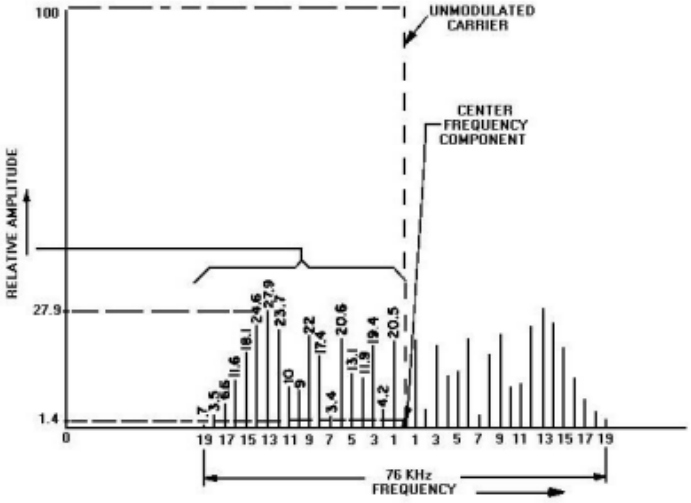


Figure 7. Another FM frequency spectrum.

(5) If an audio signal is applied to the grid of V 1, there are several noticeable effects. With zero audio voltage the RF plate current (i p) is a succession of rapid, constant-amplitude pulses. The oscillator tank would operate at a constant frequency called the NO SIGNAL or RESTING FREQUENCY. When the input audio voltage rises with a polarity that makes the grid positive with respect to the cathode, the pulses of plate current gradually increase in amplitude. This leading RF plate current is drawn through the oscillator tank and is equivalent to an increased value of tank capacitance. Thus, the oscillator frequency is lowered.

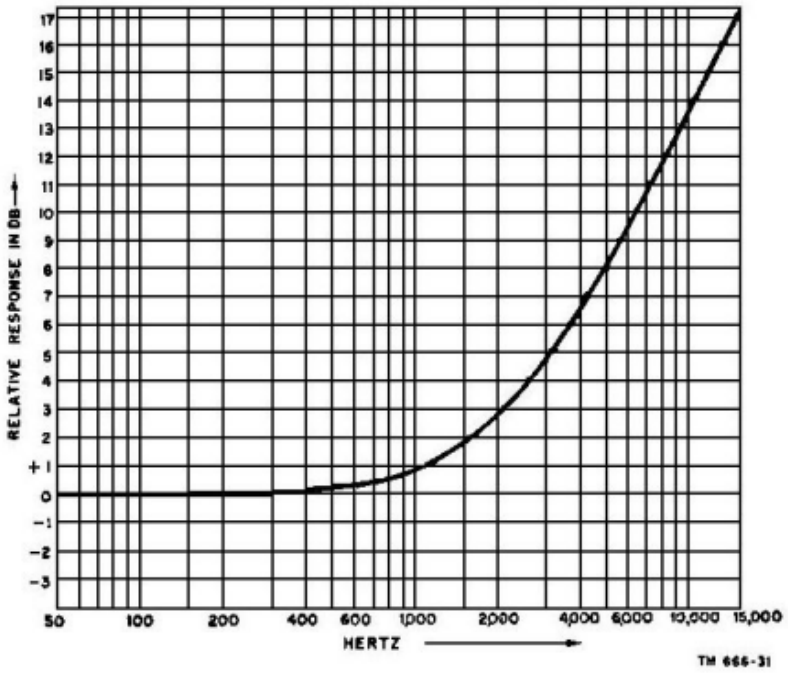


Figure 8. Pre-emphasis curve.

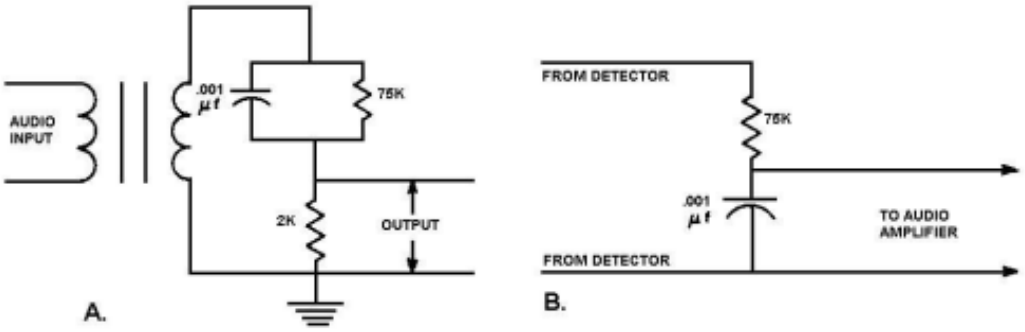


Figure 9. Pre-emphasis and de-emphasis networks.

(6) Conversely, when the input audio signal makes the grid of the reactance tube negative with respect to the cathode, the RF plate current pulses gradually decrease in amplitude and the oscillator frequency increases.

(7) The frequency of the input audio signal determines the number of times per second that the oscillator tank frequency changes. In other words, the input audio signal frequency determines the RATE of frequency deviation or how often the frequency goes above and below the carrier frequency. On the other hand, the amplitude of the input audio signal determines the AMOUNT of frequency deviation or how much the frequency goes above and below the carrier frequency. Thus, the reactance tube, with its audio signal input, produces a frequency modulated output wave.

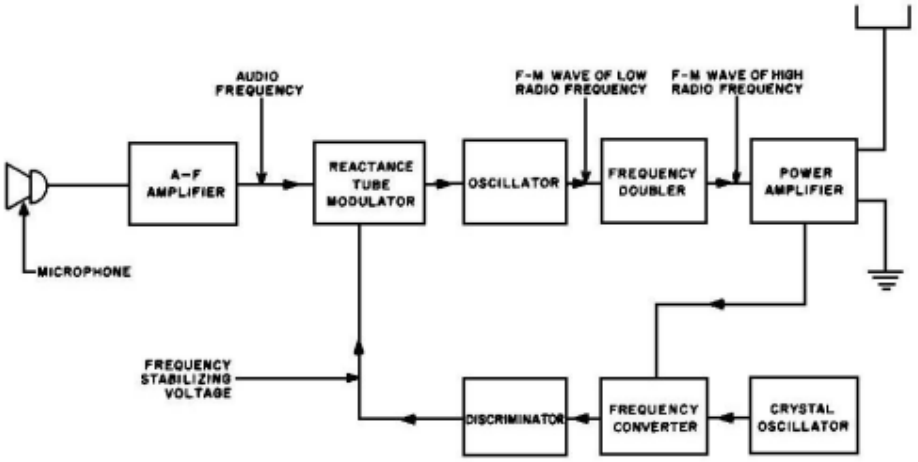


Figure 10. Block diagram of a reactance tube FM transmitter.

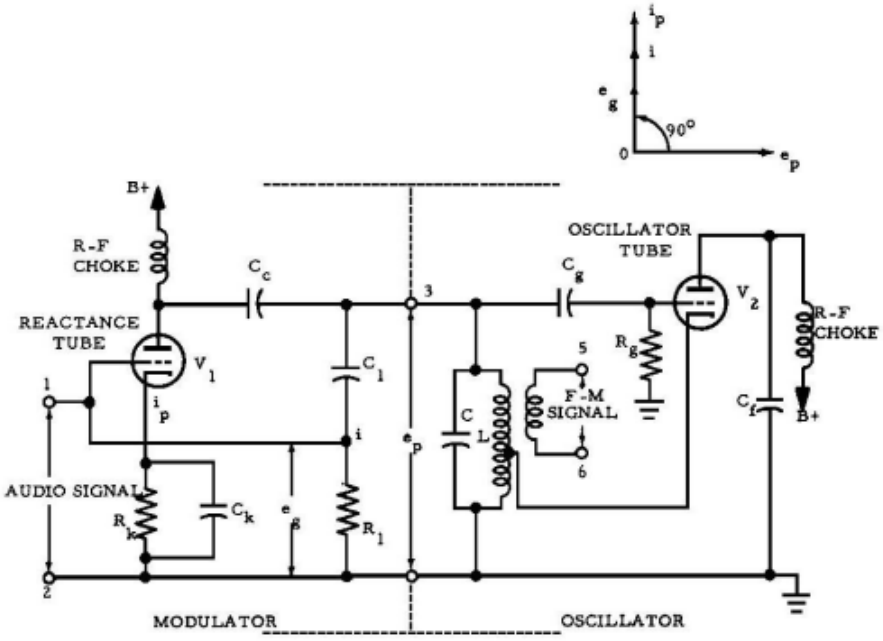


Figure 11. Basic circuit of reactance tube modulator and oscillator.

MMS SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 1

1. What is one disadvantage of an amplitude modulation communication system?

   A. It is too complicated for ready maintenance
   B. It is too expensive to maintain in the field
   C. It is highly susceptible to simple jamming systems
   D. It is highly susceptible to random noise and other interferences

2. The amount of frequency deviation is directly proportional to which signal component?

   A. Amplitude of the modulating signal
   B. Frequency of the carrier
   C. Frequency of the modulating signal
   D. Amplitude of the carrier

3. What results if the amplitude of the modulating signal is increased?

   A. A decrease in the amount of deviation of the carrier
   B. A decrease in instantaneous frequency of the carrier
   C. An increase in the amount of frequency deviation of the carrier
   D. An increase in the rate of frequency deviation of the carrier

4. What is the effect of increasing the frequency of the modulating signal?

   A. An increase in the instantaneous frequency of the carrier
   B. An increase in the rate of frequency deviation of the carrier
   C. A decrease in the amount of frequency deviation
   D. A decrease in the instantaneous frequency of the carrier

5. What factor determines the distance between sidebands?

   A. Amplitude of the modulating signal
   B. Frequency of the carrier wave
   C. Amplitude of the carrier wave
   D. Frequency of the modulating signal

6. Which BEST describes the location of the first pair of sidebands in an FM wave?

A. Carrier frequency, plus and minus the modulating frequency
B. Modulating frequency, plus and minus twice the carrier frequency
C. Carrier frequency, plus and minus twice the modulating frequency
D. Modulating frequency, plus and minus the carrier frequency

7. What is determined by the modulation index?

A. The frequency and width of sidebands
B. The frequency and amplitude of sidebands
C. The number and amplitude of sidebands
D. The number and frequency of sidebands

8. What is the modulation index of an FM wave if f d = 45 KHz, f m = 15 KHz, and f_o = 20 MHz?

A. 3
B. 6
C. 15
D. 200

9. How many significant sideband pairs are included in an FM wave that has an f d of 60 KHz, an f m of 5 KHz, and f_o of 95 MHz?

A. 6
B. 12
C. 16
D. 19

10. What is the total bandwidth, in kilohertz, of an FM wave what has an f d of 50 KHz and an f m of 5 KHz?

A. 70
B. 100
C. 140
D. 200

11. Why is a guard band of 25 KHz used in FM transmission?

A. To minimize distortion from other frequencies
B. To include most of the significant sidebands beyond the established limits
C. To preclude most of the significant sidebands beyond the established limits
D. To minimize distortion from other stations

12. What BEST describes the power contained in the sidebands?

A. It gets larger as the distance from the carrier decreases
B. It is taken from the modulating signal
C. It gets smaller as the distance from the carrier increases
D. It is taken from the carrier

13. Why is pre-emphasis used in FM?

A. To decrease the sideband spectrum for video
B. To decrease the signal-to-noise ratio of the low audio frequencies
C. To reduce the sideband spectrum for speech
D. To increase the signal-to-noise ratio of the higher audio frequencies

14. What is the function of the reactance tube modulator in an FM transmitter system?

A. To detect changes in the frequency of the FM signal index
B. To amplitude modulate a carrier in accordance with an audio signal
C. To detect changes in the polarity of the FM signal factor
D. To frequency modulate a carrier wave in accordance with an audio signal

15. What represents the ratio between the amount of frequency deviation and the frequency of the modulating signal?

A. Modulation coefficient
B. Modulation index
C. Modulation factor
D. Modulation standard

16. What is the current-voltage relationship in a reactance tube modulator circuit if the capacitive reactance of the phase shift network is larger than the resistance?

A. Current (i p) leads the voltage (e p) by approximately 90 degrees
B. Current (i) leads the voltage (e p) by 45 percent
C. Voltage (e p) leads the current (i) by approximately 90 degrees
D. Voltage (e p) leads the current (i) by 45 degrees

NOTE: Questions 17 through 19 pertain to figure 11.

17. Why is capacitor (C c) used in this circuit?

A. To block the AC
B. To block the DC
C. To control resonant frequency of the tank circuit
D. To tune the tank circuit to resonant frequency

18. What determines the frequency deviation rate of the oscillator?

A. The amplitude of the input audio signal
B. The phase relationship between the oscillator frequency and the carrier signal
C. The phase relationship between the oscillator frequency and the input audio signal
D. The frequency of the input audio signal

19. What determines the amount of frequency deviation of the oscillator?

A. Amplitude of the input audio signal
B. Amplification factor of tube V2
C. Frequency of the input audio signal
D. Frequency of tube V2

20. What unit provides for DE-EMPHASIS in an FM system?

A. Transmitter
B. Reactance tube modulator
C. Receiver
D. Frequency converter

LESSON 2. LIMITERS AND DISCRIMINATORS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, function, and use of limiters and discriminators to include parallel, saturation, and cutoff limiting circuitry.**
Lesson Credit Hours.....	**Two**

TEXT

1. GENERAL. Circuits that remove all or part of either the positive or negative portion of an input wave are called limiters or clippers. Limiters are useful in a variety of ways: they are applicable in wave shaping circuits where the extremities of the input signal are to be squared off, a sine wave can be converted into a rectangular wave by a limiter circuit, or a peaked wave may be applied to a limiter to eliminate either the positive or negative peaks from the output. Limiters can also prevent a voltage from swinging too far in either the positive or negative direction.

2. SERIES DIODE LIMITERS.

a. Diodes are very useful for limiting since they conduct current only when the plate is positive with respect to the cathode. Figure 1A illustrates a series-connected diode (load connected in series with the tube) that is used to limit the positive input cycle of a sine wave. The input voltage is denoted by e i and the output by e o. When any voltage, say 115 volts (163 volts peak value), is applied to the input terminals of the diode, the output follows the input only when the negative input cycle is applied.

b. When the positive cycle is applied, the cathode becomes positive with respect to the plate and consequently the tube cannot conduct. Since there is no current flow no voltage is developed across the 1-megohm output resistor. Therefore, the positive input cycle is limited to zero as shown by the solid line in the output. The dotted portion is the clipped or limited part of the wave.

c. When the negative input cycle is applied, the plate becomes positive with respect to the cathode and the tube conducts. The current flowing through the circuit develops a voltage across the internal resistance of the tube and the load resistor. These two resistances act as a voltage divider and divide the applied voltage, as shown by the dotted and solid portions in the negative swing of the output wave (fig 1), approximately 1/1,000 of which appears across the tube (assuming the internal resistance of the tube is 1,000 ohms) and 999/1,000 across the load resistor. Since the applied voltage is 163 volts peak, approximately 0.163 volts appears across the tube and the remainder, or about 162 volts plus, across the load resistor. Thus, except for the small drop across the tube, the output is nearly equal to the negative input. The diode has limited or clipped the positive input cycle and has virtually reproduced the negative input cycle both in shape and magnitude.

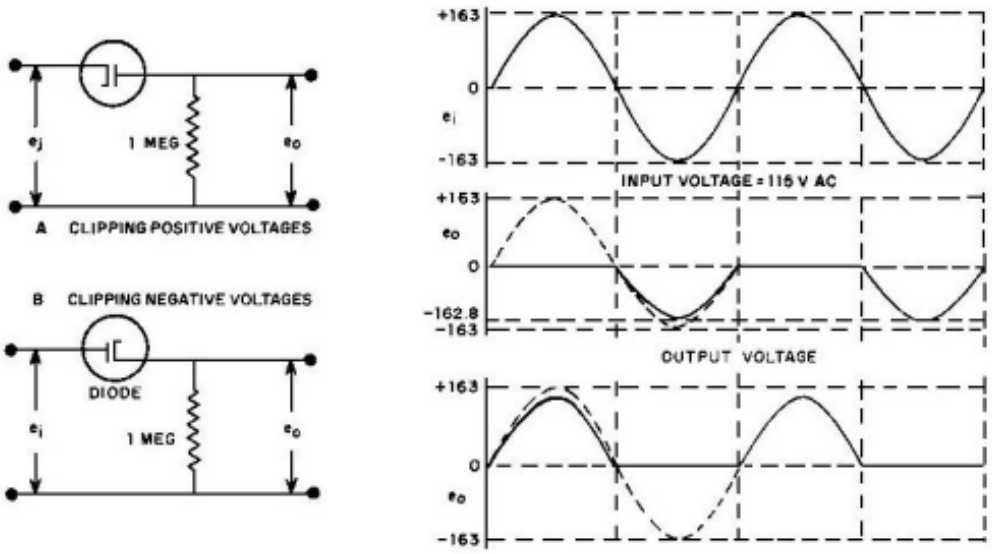


Figure 1. Series diode limiter.

d. When reversed, as shown in figure 1B, the diode limits the negative alternation of the input sine wave because the plate is negative with respect to the cathode. During the positive alternation, the tube conducts because its plate is positive with respect to the cathode. The current through the diode develops a voltage across the resistor that follows the positive cycle of the input and is equal to it except for the small drop across the tube itself. The output wave is shown by the solid line and the clipped portion by the dotted line.

3. SHUNT DIODE LIMITERS.

a. Another method of using a diode as a limiter is to connect it in parallel with the load. In figure 2A, the diode is connected to limit the positive input cycle. When the positive cycle of the input voltage is applied to the plate the diode conducts. Therefore, the current flows through a voltage divider consisting of the 1-megohm resistor and the internal plate resistance. This voltage divider divides the applied voltage with most of the voltage dropped across the 1-megohm resistor (approximately 162 volts), as shown by the dotted portion of the wave shape, and the remainder, as shown by the solid line, is dropped across the tube. Since the output terminals are across the tube, the output is very small (0.163 volts) during the time when the output cycle is positive. The output is limited or clipped to practically zero voltage during this time.

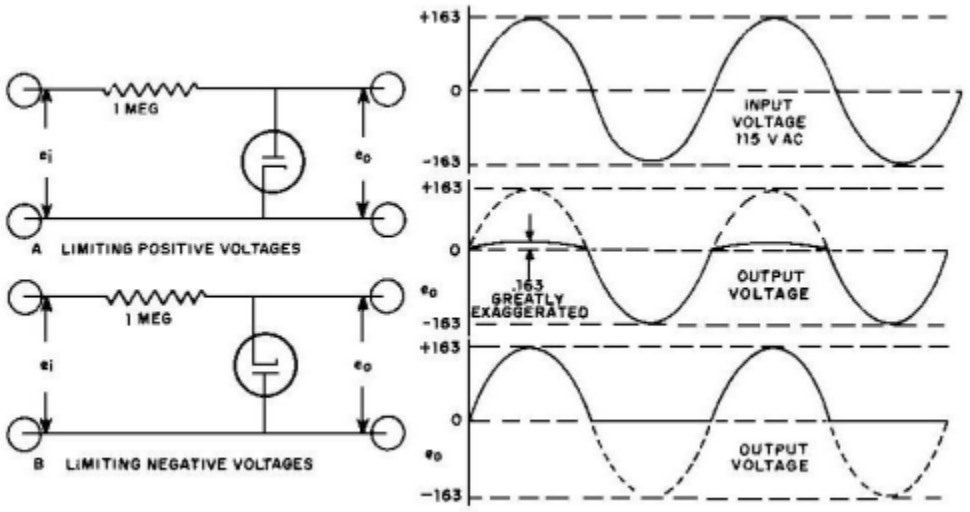


Figure 2. Shunt diode limiters.

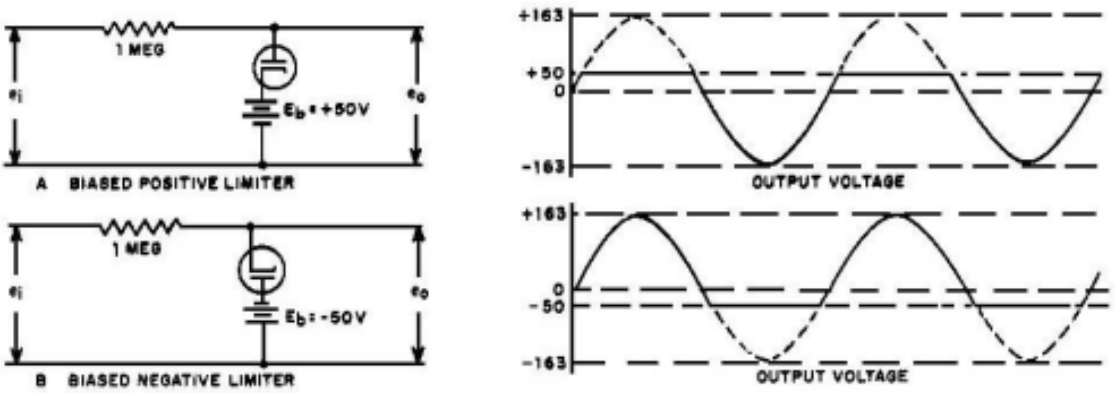


Figure 3. Maintaining voltage above certain level.

b. During the negative portion of the input cycle, the plate is negative with respect to the cathode and current does not flow. Consequently, there is no voltage drop across the resistor during this time. However, since the tube appears in an open circuit, the applied voltage appears across its output terminals. Thus, the output voltage follows, and is equal to, the input voltage during the time the negative cycle is applied to the tube.

c. The negative input cycle may be removed by connecting the tube as shown in figure 2B. When connected in this manner, the tube conducts when the cathode is negative. Since virtually all of the applied voltage appears across the resistor, only a very small amount is applied across the tube. Therefore, since the output is taken across the tube, the negative input cycle has been reduced or limited to practically zero.

4. BIASED LIMITERS.

a. The input voltage can be limited to some value other than zero by maintaining the plate or cathode at that voltage by means of a battery or a biasing resistor. Each of the limiting circuits in figure 3 employs a battery to supply a biasing voltage.

b. Circuit A (fig 3) is designed to limit the swing of the positive input cycle to +50 volts. The input voltage (e i) for these circuits is 115 volts with a peak value of 163 volts. The battery connected in the cathode circuit maintains the cathode at 50 volts positive with respect to the plate before the input is applied. As long as the input voltage is less than 50 volts the tube cannot conduct, however, as soon as the input exceeds 50 volts current will flow. During conduction time, the low resistance of the tube effectively connects the upper output terminal of the circuit to the positive terminal of the battery. Therefore, during the portion of the positive input cycle when the voltage exceeds the 50 volts on the cathode, the output voltage equals the battery voltage of 50 volts. The difference between the input voltage and this voltage (neglecting the small voltage drop across the internal resistance of the tube) appears across the 1-megohm resistor.

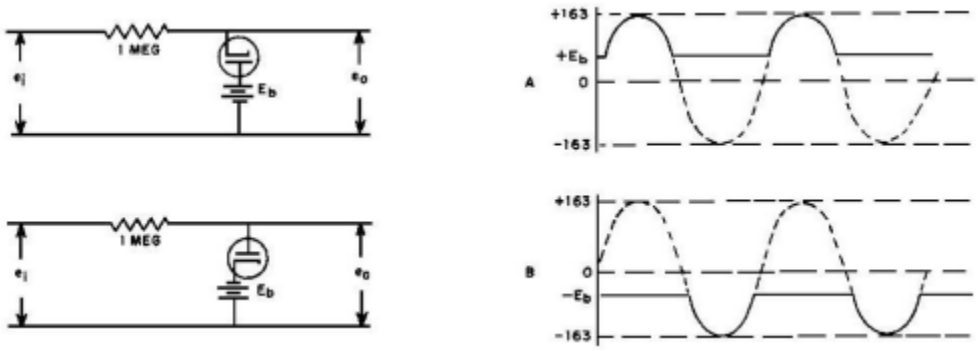


Figure 4. Limiting to other than zero.

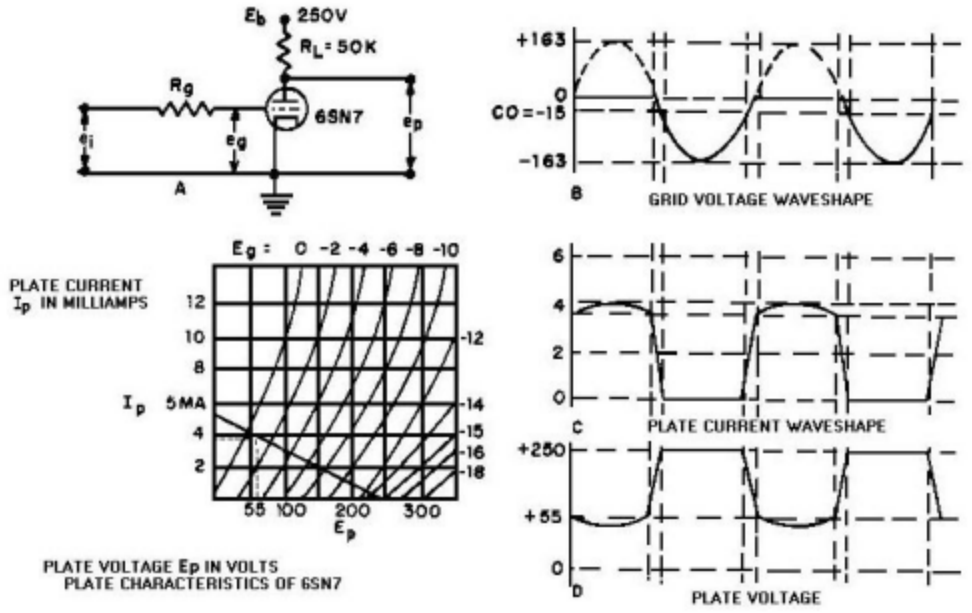


Figure 5. Grid current and grid cutoff limiting.

c. In circuit B (fig 3), battery E b in the diode plate circuit makes the plate 50 volts negative with respect to the cathode. As long as the input is positive or less negative than E b, the diode acts like an open circuit and the voltage across the output is equal to the input. When the input becomes more negative than E b, the cathode is negative with respect to the plate and the diode conducts. This connects the upper output terminal to the negative terminal of the battery. Therefore, 50 volts will appear in the output during this part of the input cycle and the rest of the 163 volts input, neglecting the small drop across the tube, appears across the 1-megohm resistor.

d. Shunt diodes may be used to limit the amount to which the input voltage can drop. In other words, only the peaks of the waveform are reproduced in the output. In figure 4, circuit A, the diode conducts during the entire part of the input waveform that is below the positive voltage of the battery. The output voltage varies between the positive level of the battery voltage and the positive extremity of the input waveform.

e. In figure 4, circuit B, the entire portion of the input waveform above the negative potential of the battery causes the diode to conduct. This produces an output voltage that varies between the negative level of E b and the negative extremity of the input. In both circuits, A and B, the difference between the value of E b and the applied voltage, during the time the diode conducts, is represented by the voltage drop across the 1-megohm resistor.

5. TRIODE LIMITERS.

a. Grid current.

(1) When a large limiting resistor is connected in series with the grid of a triode, the grid-cathode circuit may be used as a limiter circuit in exactly the same manner as the plate-cathode circuit of the shunt diode limiter. This means that when the grid is positive with respect to the cathode, the grid will attract electrons, just as the plate in a diode does, when it is positive with respect to the cathode.

(2) The limiter circuit in figure 5 is normally held at zero bias. During the positive portion of the input signal, the grid tries to swing positive. Grid current flows through the resistor (R g), developing a voltage drop with a polarity that opposes the positive input voltage. Since the input voltage must equal the sum of the drop across R g and the grid to cathode voltage, the larger that R g is, with respect to the cathode-grid resistance, the nearer the voltage on the grid is limited to that of the cathode. In figure 5 the grid is never driven more than a fraction of a voltage positive by the positive input cycle. This means that all input voltages in the positive direction are leveled off at zero.

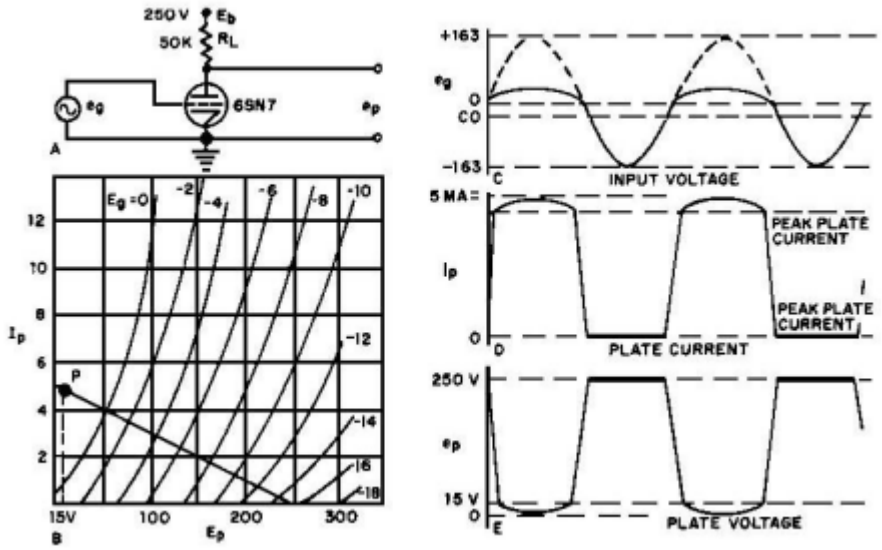


Figure 6. Saturation limiting.

b. Grid cutoff limiting. Limiting also occurs if the input voltage is great enough in the negative direction to exceed the grid voltage required to cut off the plate current. The numerical values are inserted in order that the output may be calculated. As before, the input voltage is a 115-volt sine wave and, as previously mentioned, the 1-megohm limiting resistor prevents the grid voltage from exceeding more than a fraction of a volt in the positive direction. However, the grid voltage can swing the full amount in the negative direction since no current flows from cathode to grid to reduce the applied voltage. To observe the effect of the grid voltage variation, study the loadline on the characteristic curves of figure 5. When the grid voltage is zero, the plate current is 4.0 ma and the instantaneous plate-to-cathode voltage (E p) is 55 volts. As the voltage swings in the negative direction, the plate current decreases and finally cuts off when the grid is -15 volts. Since the plate current cannot decrease below zero as the grid is made more negative, both the plate current and its resultant plate voltage become constant. This condition prevails until the grid voltage again becomes less than -15 volts. With the input wave shape (fig 5) shown, the grid voltage exceeds -15 volts for most of the half cycle. The plate voltage variation shows a rapid change to a maximum of 250 volts and remains at that value for most of the alternation. The plate voltage change is essentially a square wave, except for a slight rounding due to the grid drawing current when it is driven positive a fraction of a volt. This voltage change is amplified in the plate circuit and rounds off the square wave.

6. SATURATION LIMITING. A grid-limiting resistor is not absolutely necessary for limiting the positive half of an input cycle. If the grid is made positive by an input voltage, then there is a saturation point beyond which the plate current cannot increase. This is indicated by a dot on the loadline at P in figure 6 and is the point at which the plate resistance of the tube is assumed to be zero, and the maximum plate current obtainable then depends on the size of the plate load resistor. Actually, there is always some resistance to electron flow in the tube regardless of how positive the grid becomes. Limiting occurs at some positive value of grid voltage when the plate current and plate voltage stop changing. Therefore, saturation limiting occurs at a higher point on the grid voltage swing as compared to using a limiting resistor.

7. DISCRIMINATORS. Even though the design and, construction of radar equipment is quite exacting, the frequencies of the transmitter occasionally change. This can cause considerable trouble at the receiver, if not corrected, for if this condition occurs the receiver is no longer tuned exactly to the RF signal frequency, and signals which supply weak returns may no longer be visible on the indicator. Any change of the transmitter frequency, therefore, requires either continual readjustment of the receiver tuning by the operator or the employment of an automatic tuning device. Because constant frequency checking by the operator is time consuming and inefficient, most radar receivers employ an automatic frequency control circuit in which changes in frequency are detected by discriminator circuit. Figure 7 is a typical discriminator circuit.

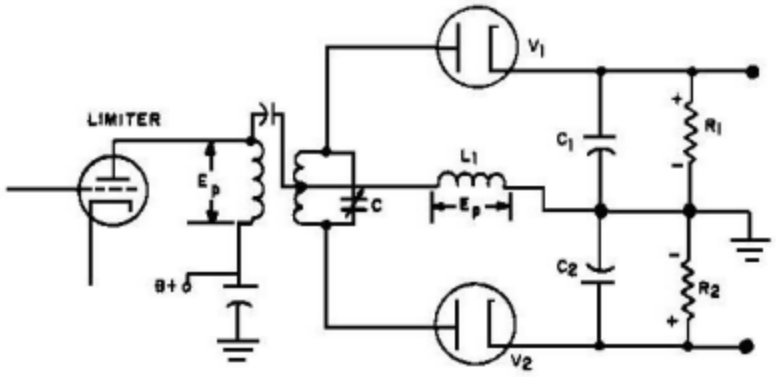


Figure 7. Discriminator circuit.

8. OPERATION AT RESONANCE.

a. The detection of a change in frequency by the discriminator is accomplished by a tuned transformer that, due to special connections, converts the frequency change into a varying amplitude change. After conversion, this voltage of varying amplitude is detected in the manner employed by any amplitude modulation detector.

b. In figure 7 note the primary and secondary of the IF transformer. The secondary is tuned to the correct frequency by capacitor C. Tubes V 1 and V 2 are diode detector tubes. The filters (R 1 C 1 and R 2 C 2) serve the same purpose as the filters in a diode detector; i.e., they remove the RF component from the circuit.

c. Since L 1 is connected across the primary, through a DC blocking capacitor, the primary voltage appears across it at all times. The connection to each diode from this choke causes the primary voltage (E p) to appear at the plates of the diodes with the same phase shift. This voltage causes currents to flow in opposite directions through the resistors (R 1 and R 2) resulting in a zero output voltage.

d. The phase relationship of the voltage across the RF choke, as compared to the voltage induced in the secondary, is the key to the operation of the discriminator circuit. For this reason you should make a detailed analysis of figure 8 which shows the discriminator-input (A) and the vector relationships of the current and voltages (B).

e. At the resonant frequency the primary voltage (E p) is the reference vector. Since the mutual inductance (coupling) is small, the primary is inductive and the primary current (I p) will lag E p by 90 degrees. The magnetic field, which affects the secondary (called flux and shown by the symbol ϕ), is in phase with the primary current. Due to normal transformer action, the voltage induced in the secondary is 90 degrees behind the flux.

f. The induced voltage (E i) is simulated by a generator in the equivalent circuit shown in figure 9. The generator is inserted at the center of the transformer secondary where the voltage is divided between the two tubes. A current (I s) flows around the loop, which is composed of the secondary windings and the capacitor (C). This loop is a series-resonant circuit as far as the generator is concerned. Since the circuit is at resonance, the current I s is in phase with the induced voltage.

g. Each half of the secondary has considerable inductive reactance at the radio frequency. Therefore, there is a voltage drop across this reactance due to I s. These voltages are shown in figure 9 in the secondary circuit as E 1 and E 2. Since voltage leads the current by 90 degrees in an inductor, E 1 and E 2 are 90 degrees out of phase with I s. E 2 actually leads I s as it should, but E 1 appears to be lagging by 90 degrees. Current flows in the same direction through both coils, with the vector voltages being measured in respect to the center of the secondary coil. At any instant of time, this causes E 1 and E 2 to be 180 degrees out of phase with each other and makes one voltage lead and the other lag I s by 90 degrees.

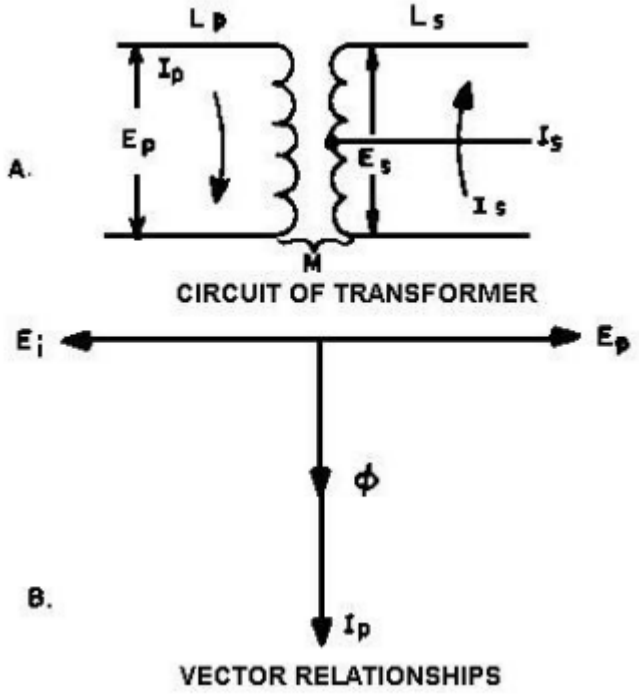


Figure 8. Transformer vector relationships and waveshapes.

h. Note in figure 10, diagram A, (the equivalent circuit of the discriminator in which the voltages are replaced by generators) that the plate voltage on V 1 is the sum of the voltages E p and E 1, and that the plate voltage on V 2 is the sum of E p and E 2. The vector diagram B shows E p and E 1 added vectorially to produce a vector sum E v1, which is the actual plate voltage on V 1. When the plate current flows, C 1 charges to near the peak voltage of E v1, thus, producing a constant DC voltage across R 1 that is almost equal to E v1. In the same manner, E p and E 2 add to produce E v2, the plate voltage on the other diode. Consequently, C 2 charges to E v2 and a constant voltage almost equal to E v2 appears across R 2. The vectors are shown in diagram C.

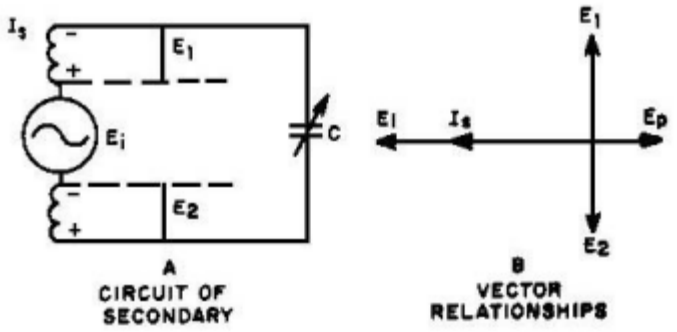


Figure 9. Secondary voltages at resonance.

i. Observe that the voltages across the filters (R 1, C 1 and R 2, C 2) are DC voltages. Obviously, phase relationships will not exist and, in this case, only amplitude relationships are important. Since E p is common to both tubes, and E 1 equals E 2, the vector sums of E v1 and E v2 are equal. The vector illustrations show that the resultants of the sine waves have equal amplitudes, although their phases are different. The DC voltages across the filters are equal but have opposite polarities; therefore, the sum of these voltages between X and Y will be zero. This fact indicates that the output of a discriminator is zero at resonance.

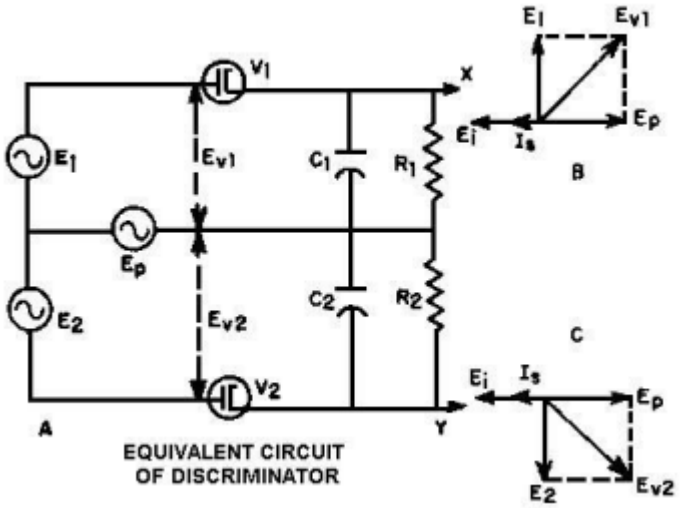


Figure 10. Resultant plate voltages at resonance.

9. OUTPUT AT FREQUENCIES BELOW RESONANCE.

a. When the input frequency is lower than the center, or resonant frequency, the output is no longer zero. With the primary voltage used as a reference the voltage induced in the secondary is still 180 degrees out of phase, as shown by the vector diagrams in figure 11. As the frequency decreases, capacitive reactance increases and inductive reactance decreases. Therefore, the secondary circuit of the transformer in figure 9, diagram A, will be capacitive at frequencies below resonance. The current (I s) in a capacitive circuit leads the applied voltage (E i).

b. An arbitrary amount of lead, or angular displacement, is used in vector diagram A of figure 11. The voltage drops, E 1 and E 2, will still be 90 degrees out of phase with the current since it is not a function of frequency. Under these conditions, voltage E 1 is more than 90 degrees away from E p. When added vectorially, their sum will be a value less than that at resonance even though the magnitude of the components E p and E 1 has not changed. At the same time, E 2 is less than 90 degrees away from E p, or more nearly in phase, and the magnitude of the resultant E v2 is greater than at resonance. Since the resistor voltages are proportional to the length of the resultant vectors, there will be a high voltage across R 2 and a lower voltage across R 1. The output voltage will be equal to the R 2 voltage minus the R 1 voltage. Therefore, the output point X, figure 10, diagram A, will be negative with respect to Y.

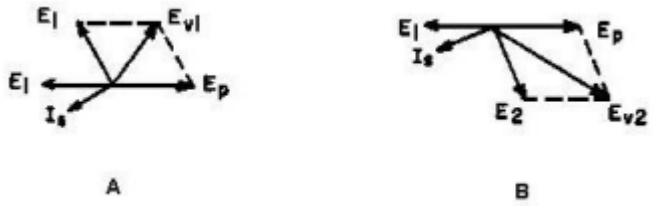


Figure 11. Voltages at frequencies below resonance.

c. It can be seen from the vector diagrams that the greater the deviation from resonance, the greater the output voltage.

10. OUTPUT AT FREQUENCIES ABOVE RESONANCE.

a. When the input frequency is greater than the center frequency, the secondary circuit is inductive and the current (I s) lags the induced voltage. Figure 12 shows the vector relationship of voltages at frequencies above resonance. Note that at frequencies above resonance that E 1 is more nearly in phase and E 2 is more out of phase with E p. Also notice that E v1 has a greater magnitude than E v2. Therefore, the DC voltage across R 1 is greater than that across R 2 and, consequently, the output voltage is positive.

b. Remember that a frequency above resonance causes a positive output at X with respect to Y (fig 10). At resonance the output is zero, and below resonance the output is negative.

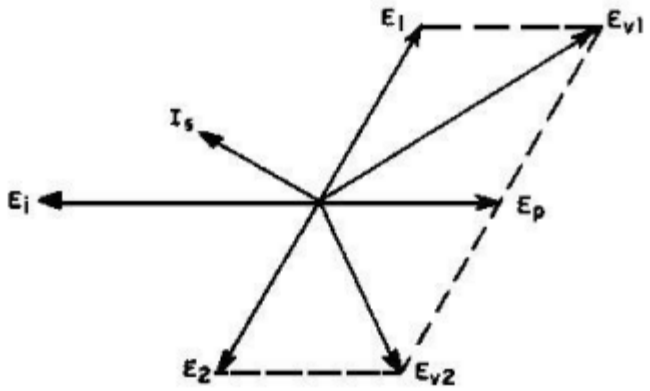


Figure 12. Voltages at frequencies above resonance.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 2

1. Why are diode tubes normally used in limiting circuitry?

   A. Because they conduct only when the grid is negative with respect to the plate

   B. Because they conduct only when the cathode is negative with respect to the plate

   C. Because they conduct only when the cathode is positive with respect to the plate

   D. Because they conduct only when the grid is positive with respect to the plate

2. What is the correct output wave shape produced by the limiter in figure 1?

   A.

   B.

   C.

   D.

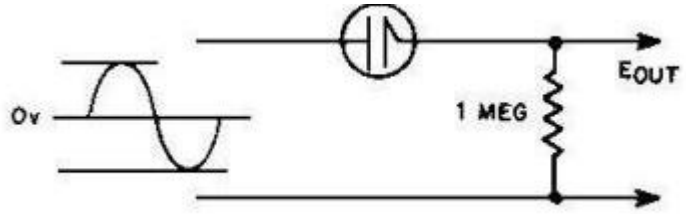
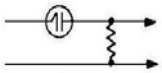
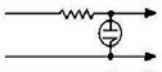


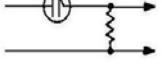
Figure 1.

3. Which diagram depicts a positive series limiter?

   A. 

   B. 

   C.

   D. 

4. Approximately how many volts will be dropped across the diode in figure 2?

A. 14.1

B. 0.141

C. 2.82

D. 28.2

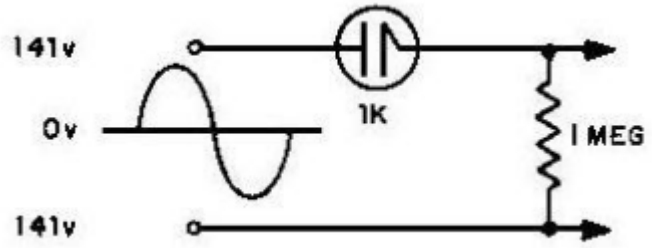
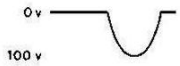
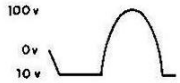
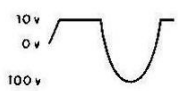


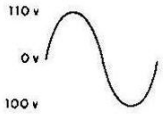
Figure 2.

5. What is the correct wave shape output in figure 3?

A. 

B. 

C. 

D. 

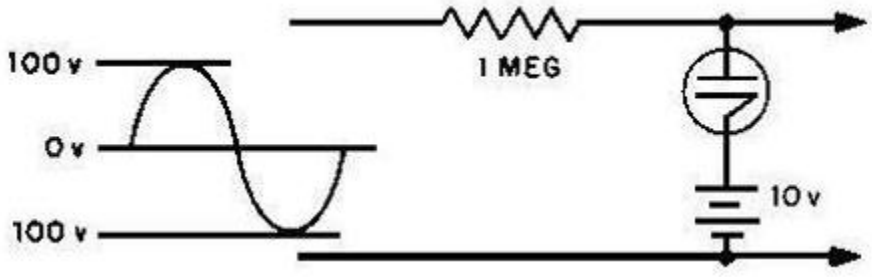


Figure 3.

6. In figure 4, when will the diode conduct?

A. During the entire positive alternation

B. Only when the input goes more positive than +15 volts

C. Only when the input goes more negative than -15 volts

D. During the entire negative alternation

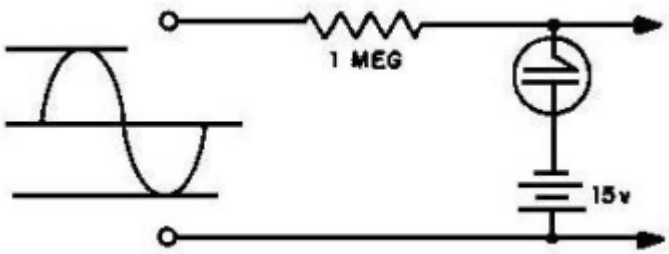


Figure 4.

7. What is the waveshape output in figure 5?

A.

B.

C.

D.

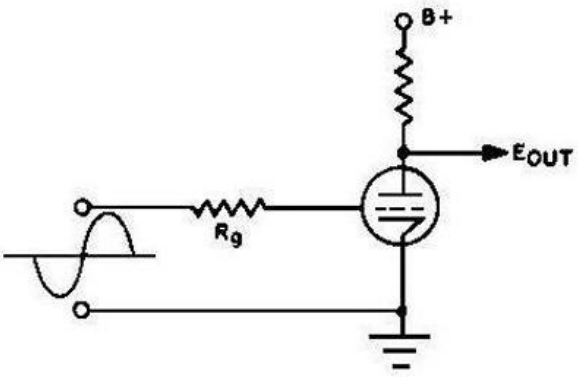


Figure 5.

8. What is the output in volts, if the tube filaments opened in figure 6?

A. 20

B. 40

C. 260

D. 300

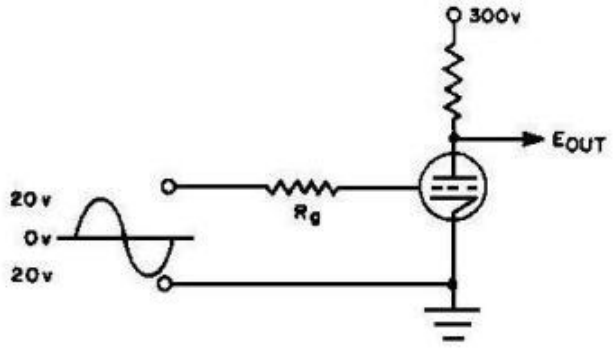


Figure 6.

9. What is the purpose of the grid limiting resistor (R_g) in figure 7?

A. To limit the negative swing of input

B. To limit the cutoff potential of the tube

C. To limit the positive alternation of input

D. To limit the saturation potential of the tube

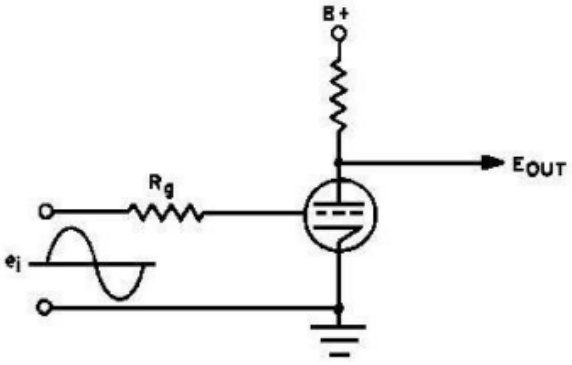


Figure 7.

10. When is the transformer secondary circuit of a discriminator mainly inductive?

A. Below resonance

B. Above resonance

C. At saturation

D. At cutoff

11. What is the function of a discriminator?

A. To detect changes in frequency

B. To convert changes in frequency to frequency variations

C. To detect changes in amplitude

D. To convert changes in amplitude to frequency variations

12. What is the current-voltage relationship of a discriminator at resonance?

A. I s leads E i by 90 degrees

B. I s is 180 degrees out of phase with E i

C. I s is in phase with E i

D. I s lags E i by 90 degrees

13. What is the purpose of R 1 and C 1 in figure 8?

A. To act as a high frequency bypass filter network

B. To act as a low frequency bypass filter network

C. To retain the RF component

D. To remove the RF component

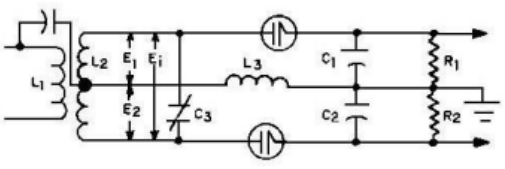
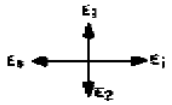
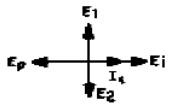
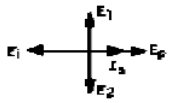


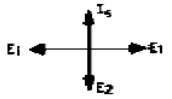
Figure 8.

14. In figure 8, what is the discriminator output vector if the circuit is at resonance?

A. 

B. 

C. 

D. 

15. How is capacitive reactance affected if frequency is doubled?

A. Decreased by ½ π

B. Halved

C. Increased by 2 π

D. Doubled

16. What BEST describes the discriminator secondary tank circuit below resonance?

A. It is resistive

B. It is capacitive

C. It is inductive

D. It is conductive

17. What is the discriminator output at resonance?

A. Peak

B. DC varying according to input amplitude

C. Zero

D. DC varying according to input frequency

18. What is the discriminator output above resonance?

A. An AC voltage whose amplitude is determined by the amount of frequency deviation from resonance

B. A DC voltage which is dependent upon the magnitude of the input signal

C. An AC voltage determined by phase relationship of the secondary circuit

D. A DC voltage whose amplitude is determined by the amount of frequency deviation from resonance

19. What is the vector relationship of a discriminator below resonance?

A. E s leads E p

B. E i leads I s

C. I s leads E I

D. E s lags E p

20. Which receiver circuit normally used a discriminator?

A. Local oscillator

B. Automatic frequency control

C. Remote oscillator

D. Automatic voltage control

LESSON 3. SPECIAL PURPOSE OSCILLATORS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, function, and use of special purpose oscillators, such as the blocking and shock-excited oscillators.**
Lesson Credit Hours.....	**Two**

TEXT

1. GENERAL.

a. The use of narrow pulses in various radar circuits is very common. Synchronized pulses, with frequency controlled, are used in radar to accomplish the synchronized triggering of many circuits. To accurately measure the distance to a target, it is essential that the sweep circuit and the transmitted pulse be synchronized; i.e., triggered at the same time, or at definitely related times.

b. Narrow pulses may be used to synchronize the sweep circuit with the transmitter pulse. These narrow pulses are applied to different circuits causing them to operate simultaneously. Regardless of how the pulses are applied and regardless of their polarity, a circuit that generates very narrow pulses at a controlled frequency is a necessity in modern radar equipment. One special circuit that produces these synchronized, narrow pulses is the blocking oscillator.

2. CHARACTERISTICS.

a. A blocking oscillator may be either a free running or a synchronized (triggered by an outside source). The free-running blocking oscillator generates a series of narrow pulses at a frequency determined by the constants of the circuit. A synchronized blocking oscillator generates a series of narrow pulses at a frequency determined by the frequency of the external-synchronizing signal. The frequency of the blocking oscillator output pulses is either the same as the synchronizing signal or a submultiple of it.

b. Referring to figure 1, we see that it includes a triode having the primary of a step-down transformer (approximately 3:1) in its plate circuit. The transformer serves as a feedback source, which aids conduction. The secondary of the transformer is coupled through a capacitor to the grid. Also, the transformer is wound so as to give a 180-degree phase shift between its primary and secondary coils.

3. CIRCUIT OPERATION.

a. When power is applied a current starts flowing through the tube toward B+. This causes an electromagnetic field to build up around the primary (L p) of the transformer with a polarity as shown in figure 2. As the field builds up, lines of flux will cut the secondary coil (L s) and induce a voltage of opposite polarity, as compared to the primary coil. Since a capacitor acts as an instantaneous short to a change in voltage, the induced voltage of L s is felt immediately on the control grid. The induced positive voltage causes the tube to conduct harder and the control grid to draw current. The capacitor starts charging to the positive potential induced in the secondary of the transformer.

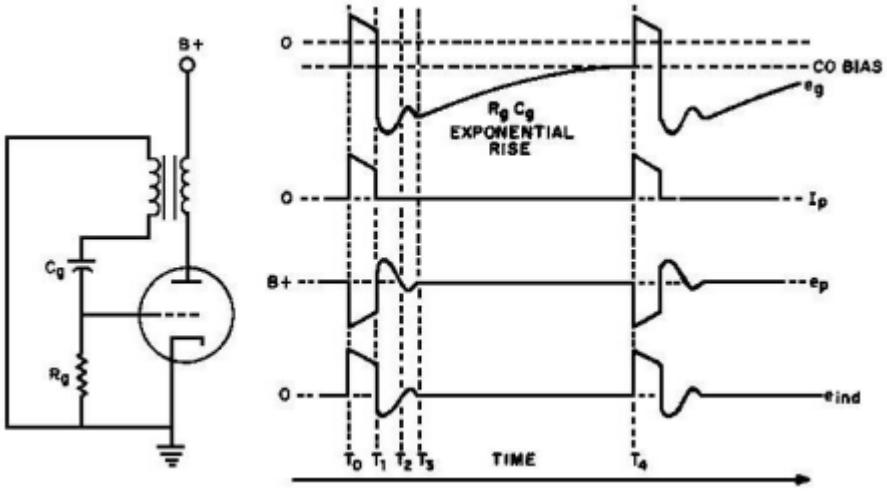


Figure 1. A basic blocking oscillator and waveshapes.

b. When plate current flowing through L p becomes constant, there will be no changing flux lines to sustain the secondary potential. Once the induced, positive potential of the secondary is removed, the capacitor will start discharging (fig 3). The discharging current develops a negative voltage at the top of resistor (R g) in respect to ground. The negative voltage will exceed the cutoff potential of the tube and current will cease flowing. The length of time the tube is cut off depends upon the RC time constant of R g and C g. As soon as the capacitor has discharged to a point more positive than the cutoff potential of the tube, current will flow again and the above cycle is repeated.

4. ANALYSIS OF WAVESHAPES.

a. Referring to figure 1, the tube begins to conduct at time T 0. Note that the plate current rises very quickly, the grid becomes positive, and the plate voltage is driven in a negative direction from B+ toward zero. As soon as the plate current reaches an unchanging value, the induced voltage will fall to zero. This is exactly what would happen if no current flowed in the secondary. The induced voltage, however, is of such polarity as to make the grid draw current. Due to the capacitor, charging grid current flows at an exponential rate. Current is greatest during the first instant, but decreases toward zero as the capacitor charges. This changing grid current will explain the three waveshapes (fig 1) between T 0 and T 1.

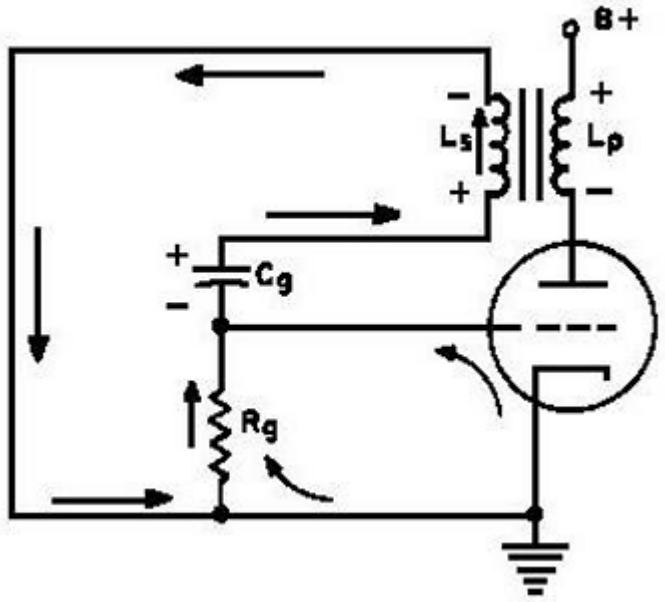


Figure 2. Capacitor charge path.

b. At time T 1, plate current (I p) becomes steady and the induced voltage of the secondary falls to zero due to steady flux lines. Instantaneously, the secondary field collapses, reverses polarity, and acts as a series battery aiding the discharge of C g. As C g discharges, it develops a negative voltage across R g that immediately cuts off tube current. The magnitude of this instantaneous negative drop is equal to the sum of the voltage across the capacitor and the induced voltage of the secondary. This effect is shown in the waveshapes(fig 1) at time T 1. At this time the grid voltage has dropped below cutoff, plate current decreases to zero, and the plate voltage rises above B+. This is due to the collapsing field of the primary reversing its polarity (fig 3), and series-aiding B+. As the field around the primary coil collapses it induces a voltage into the secondary of the opposite polarity as before, and causes the oscillatory action seen between times T 1 and T 3 (fig 1). By time T 3, C g is discharging at an exponential rate toward zero. E g starts rising toward the cutoff potential at an exponential rate determined by the values of R g and C g. When the grid voltage reaches the cutoff bias at time T 4 (fig 1), the tube again starts conducting. From this time on the action is repeated with a consequent repetition of waveshapes across the various components.

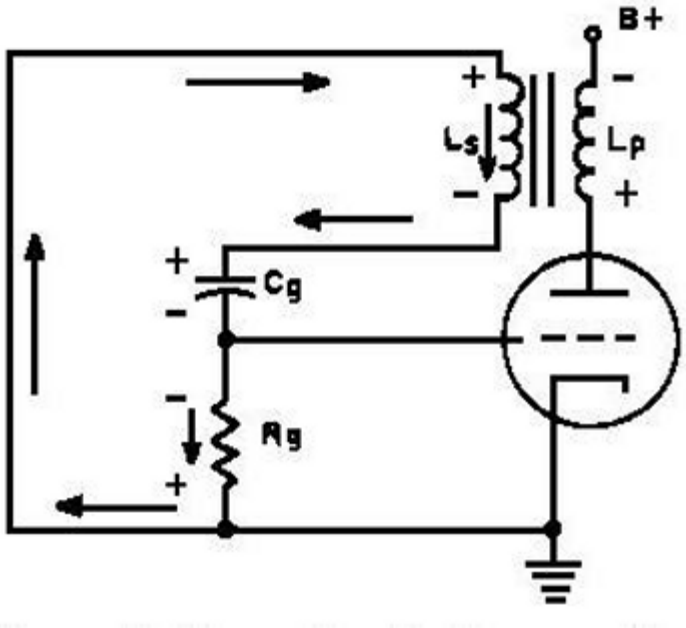


Figure 3. Capacitor discharge path.

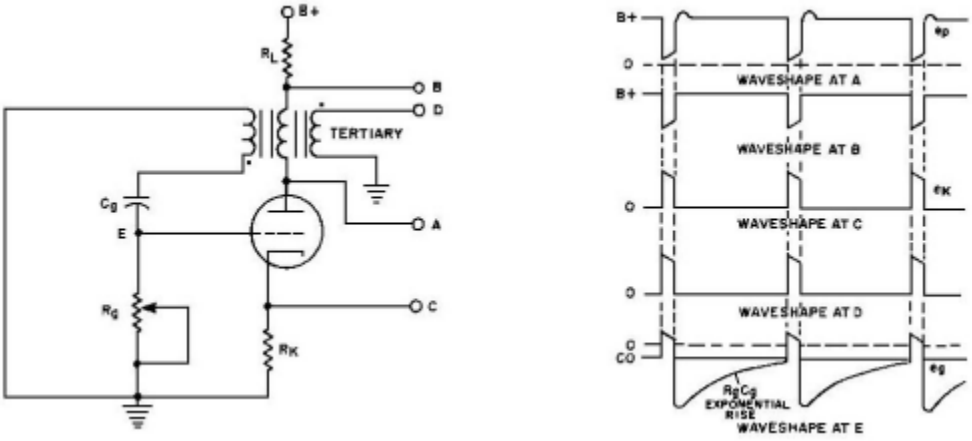


Figure 4. Blocking oscillator with R g variable and waveshapes.

5. FACTORS THAT AFFECT FREQUENCY.

a. If an output is taken from plate to cathode, the waveshape (e p) (fig 1) represents the output wave of the blocking oscillator. If damped oscillations are disregarded, the output may be considered as a series of negative-going pulses generated each time the tube conducts. This is followed by a period of nonconduction when the plate voltage is at B+. Since the tube conducts for a very short duration, the time of nonconduction may be considered as the time (period) of a complete cycle. Hence, the frequency, which is a reciprocal of the period T, is dependent upon the period of nonconduction. The factors that determine how long the tube is not conducting (cutoff) are:

(1) The critical drop, reflected as a negative voltage on the grid, that occurs immediately after conduction.

(2) The magnitude of the damped oscillations that occur immediately after the initial drop.

(3) The cutoff value of the tube.

(4) The value of R g and C g that determines the exponential rise of the grid waveshape toward the cutoff value.

b. The first three factors depend upon the value of B+, the characteristics of the tube, and the transformer used. Once these circuit components are chosen, they are not readily variable as a means of controlling the frequency of the pulses. The fourth factor depends upon the values of C g and R g, which may readily be made variable. As shown in figure 4, R g is usually made variable for controlling the output frequency of a blocking oscillator.

c. The effect of increasing R g is shown in figure 5. As R g is increased, the charge on C g leaks off more slowly and the tube remains cut off for a longer period. C g is not usually employed to vary the output frequency because it also has an effect on the width of the pulse or conducting time. For example, if the capacitance of C g was decreased, it would charge up faster, plate current would reach a steady state sooner, and the conducting pulse would be more narrow.

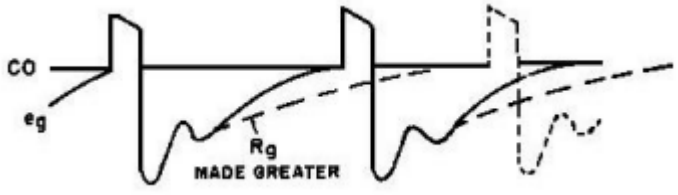


Figure 5. Effect of varying R g on frequency.

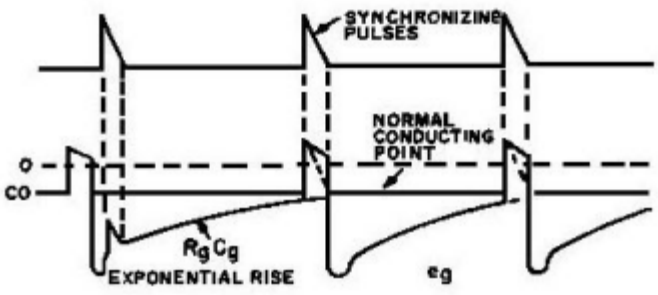


Figure 6. Synchronizing a blocking oscillator.

d. Notice in figure 4, that, in addition to making R g variable, the following additional components have been added:

(1) R k is a cathode resistor whose value is low and across which an output can be taken or it can be used to control the pulse width.

(2) R L has been placed between B+ and the primary winding to develop an output at point B free of undesirable oscillations. (In some cases, resistances of small value may be shunted across the transformer windings to suppress oscillations.)

(3) The transformer has three (tertiary) windings across which an output may be taken.

e. The output waveshapes of a blocking oscillator, with most of the undesirable oscillations suppressed, is shown in figure 4. Outputs may be taken from several points; e.g., positive from points C, D, and E, and negative from points A and B. R L has reduced the oscillations in the plate and a smoother voltage rise is noted on the grid.

6. SYNCHRONIZATION.

a. The natural frequency of a blocking oscillator will vary over a period of time due to the aging of components and the effects of temperature. Even after a thorough warm-up, it exhibits a tendency of instability. Synchronizing pulses, from an external source, are often used to counteract these tendencies of instability. The external synchronizing trigger may be injected at one of three places, but must always be of a higher frequency than the natural free-running frequency of the blocking oscillator.

b. Generally, synchronization is accomplished by applying positive synchronizing pulses to the grid of the tube. The frequency of the external pulse will be greater than that of the blocking oscillator as can be seen in figure 6. Notice that the grid voltage (e g) is the sum of E c plus the positive synchronizing pulse. Without the synchronizing pulse, the tube would not conduct until the grid voltage had risen to the cutoff point. However, with the synchronized pulse applied to the grid the tube conducts earlier. This is due to the fact that the sum of e g and the synchronized pulse is sufficient to drive the grid above cutoff, thereby speeding up conduction time. The frequency of the blocking oscillator is now the same as that of the external synchronizing pulse.

c. Blocking oscillators may also be synchronized by applying negative pulses to the cathode or by coupling the synchronizing pulse, through a tertiary winding of the plate transformer, to the grid. All of these methods are used in circuit stabilizing.

7. SHOCK-EXCITED OSCILLATOR.

a. A shock-excited oscillator is a type of oscillator that employs a vacuum tube as a switch for interrupting the steady flow of plate current through a resonant L C tank circuit as a means of exciting oscillations in the tank. This oscillator is used in operations which require periodic oscillations of a certain frequency occurring over short intervals of time. As a result of these periodic oscillations, it is sometimes called a ringing oscillator.

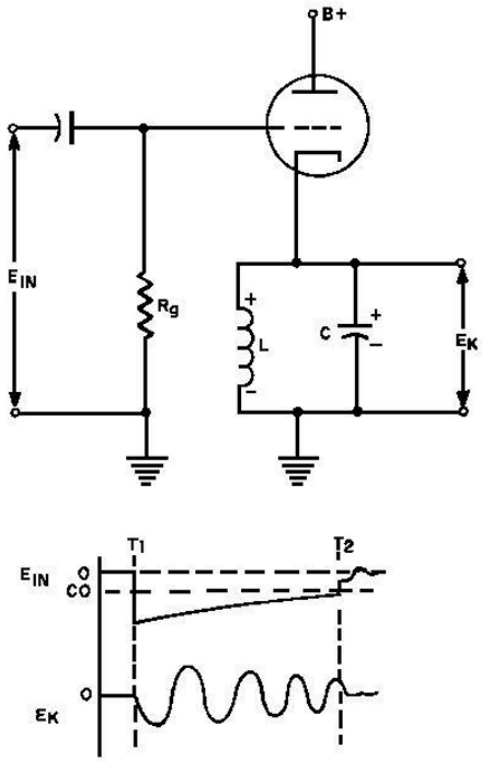


Figure 7. Shock-excited oscillator.

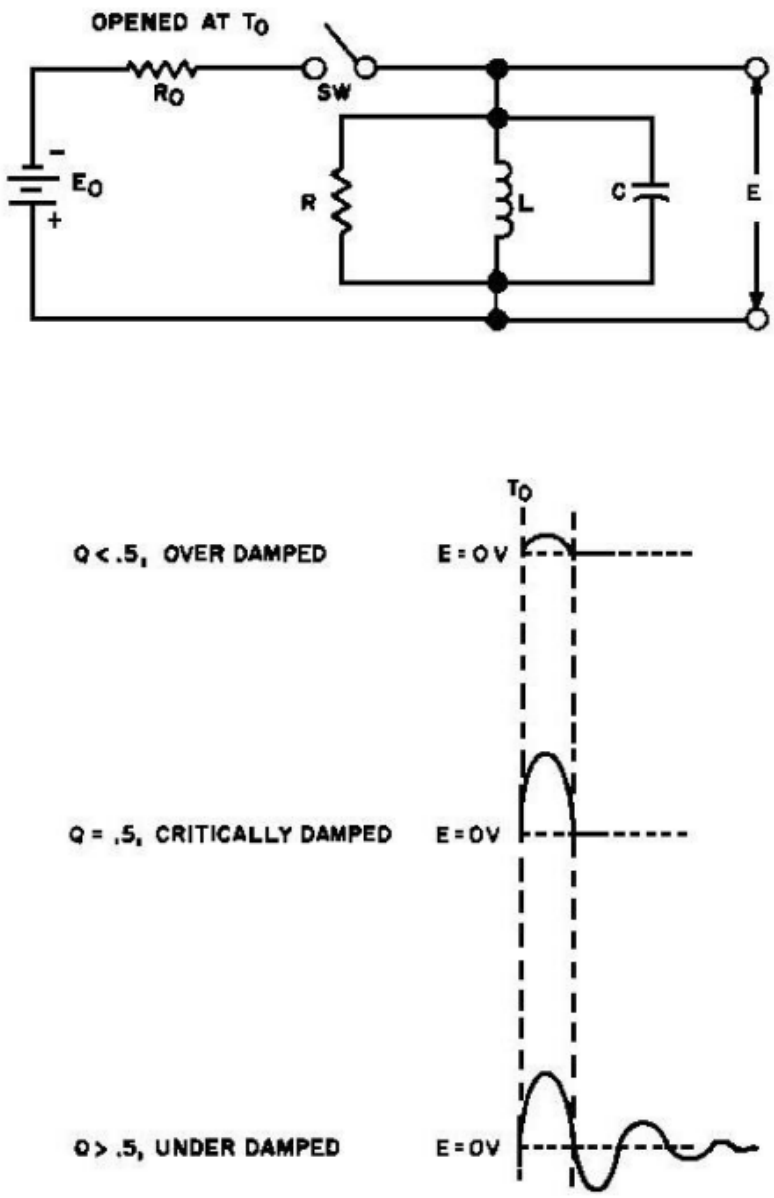


Figure 8. R-L-C transients.

b. The shock-excited oscillator has been used in radars for range measurement operations. At the time the transmitter generates a pulse, transient oscillations are generated by a shock-excited-type oscillator. These oscillations will continue for the duration of the range sweep, with the frequency dependent upon the size of L and C (fig 7). Since the frequency of the tank is known, the time between oscillations can be computed. This time between peaks is converted to radar miles and then fed to a scope for display as range pips. At the end of the range sweep, the range pips or oscillations are damped out. This damping occurs during retrace time of the scope when nothing should be displayed on the indicator.

c. Another use of the shock-excited oscillator is in a peaker circuit. Here the sine wave output of the oscillator is used to overdrive an amplifier stage having a low Q resonant tank. The amplifier produces very sharp, narrow peaks at a rate controlled by the voltage applied to its grid by the oscillator. The peaked output may then be used as a trigger or modulator pulse.

8. CIRCUIT OPERATION.

a. Referring to figure 7, notice the input and output waveforms of the voltages applied and produced. Prior to any input voltage, the tube conducts and a steady current flows through it and inductance L. Also, at this time, the capacitor is charged to the DC voltage across the coil. At time T 1, the transmitter applies a negative gate pulse to the grid of the tube, cutting it off. As current ceases to flow, the flux lines built up around L begin to collapse. As they collapse the polarity of L reverses and the coil acts like a battery, trying to keep current flowing in the same direction. The capacitor, with a tendency to equalize charges between its two plates, starts charging to the full potential across inductor L. When the capacitor is fully charged there is no more current flow.

b. With the tank circuit in the cathode, the first alternation out of the tank is negative going as shown in figure 7. As soon as the capacitor is fully charged and the tank current has ceased flowing, the capacitor begins discharging. As electrons leave the top plate of the capacitor and move toward the bottom plate, the output becomes more positive. When the capacitor discharges, current flows through the inductor, building up an electromagnetic field which aids and reinforces the oscillatory action of the tank. The building up and collapsing flux lines, coupled with the action of the capacitor, produce sinusoidal oscillations. The losses in the L C circuit are made as small as possible, so that the amplitude of oscillations will remain nearly constant for the duration of the input gate pulse. At the end of the gate pulse (time T 2, fig 7) the tube again begins conducting and tries to oscillate. However, the conducting tube is equivalent to a resistance shunted across the L C circuit, which dampens the oscillations very quickly.

c. When the shock-excited oscillator is used as a peaker circuit, all of the oscillations are damped except for the first alternation. This is accomplished by adding a resistor in parallel with the tank circuit (fig 8). Normally, the ability of a tank circuit to oscillate is determined by its Q; Q being described as the relationship between the reactance of the coil (X L) and the parallel resistor (R). The formula for the Q of a tank circuit, with the resistor in parallel, is: $Q = R/X\ L$. If R is high, then Q will be correspondingly high. Changing the size of R determines the amount of current flowing through the coil and, therefore, the number of oscillations. In figure 8 we see that if Q is greater than 0.5, it is considered to be high and the tank circuit is underdamped. If the relationship between R and X L is equal to 0.5, it is said to be critically damped or at the optimum damping point. When Q is less than 0.5, it is said to be overdamped.

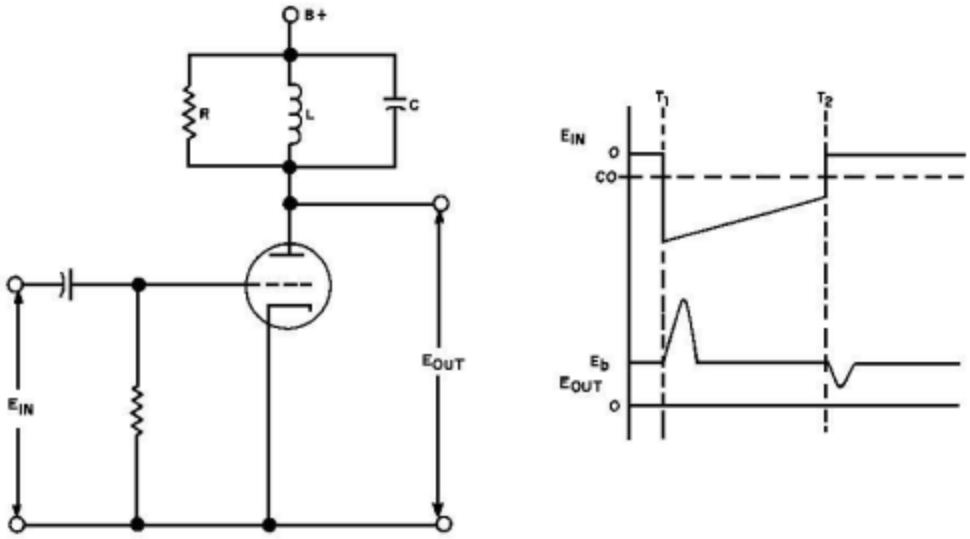


Figure 9. R-L-C peaker.

d. The R-L-C peaker circuit shown in figure 9 is actually another form of a shock-excited oscillator. The capacitance is usually not a physical component, but rather the distributed capacitance in the circuit. A resistor is connected across the L C circuit to produce nearly critical damping when the tube is cut off. Therefore, instead of oscillations, a single sharp positive peak is produced at time T 1 (fig 9), and a negative peak at time T 2. The negative peak is smaller than the positive peak because of the additional damping provided by the conducting tube after time T 2.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 3

1. What is the result if the size of the capacitor C g is increased (figure 2 of the text)?

   A. The cutoff time will decrease

   B. The conduction time will decrease

   C. Cutoff time will increase

   D. The conduction time will increase and cutoff time will decrease

2. What is normally used as the synchronizing trigger in a blocking oscillator?

   A. Positive pulses on the cathode

   B. Negative pulses on the grid

   C. Positive pulses on the plate

   D. Positive pulses on the grid

3. What frequency ratio is used as the synchronizing trigger of a blocking oscillator?

   A. Slightly higher than the free-running frequency of the blocking oscillator

   B. One-half the free-running frequency of the blocking oscillator

   C. Slightly lower than the free-running frequency of the blocking oscillator

   D. One-fourth the free-running frequency of the blocking oscillator

4. What results when an external synchronizing trigger is applied to a blocking oscillator?

   A. The output frequency decreases

   B. The output amplitude increases

   C. The output pulse width decreases

   D. The output frequency increases

5. How does the capacitor in the grid circuit of a blocking oscillator act to the sudden change in voltage produced by regenerative feedback?

   A. Instantaneous open

   B. Instantaneous short

   C. Long time constant

   D. Short time constant

6. What is the purpose of the resistor R L (figure 4 of the text)?

   A. Decrease the output frequency

   B. Increase the output frequency

   C. Aid oscillation

   D. Develop an output free of oscillations

7. What controls the output frequency of a shock-excited oscillator?

   A. Size of R and C

   B. Duration of the negative input

   C. Size of L and C

   D. Amplitude of the negative input

8. What controls the number of output oscillations illustrated in the shock-excited oscillator diagram (figure 7 of the text)?

   A. Power supply voltage

   B. Duration of the positive input

   C. Duration of the negative input

   D. Signal bias voltage

9. What is expressed by the Q of a tank circuit?

   A. The relationship between the reactance of the coil X L and R

   B. The relationship between the input and output voltages

   C. The relationship between the reactance of the coil XC and R

   D. The relationship between the input and output frequencies

10. What BEST describes the output voltage (figure 7 of the text)?

   A. Oscillates around zero volts, with the first alternation positive going

   B. Oscillates around B+, with the first alternation negative going

   C. Oscillates around B+, with the first alternation positive going

   D. Oscillates around zero volts, with the first alternation negative going

11. What is the Q of a shock-excited oscillator tank circuit if R = 18k, X L = 3k, and XC = 2k?

   A. 3

   B. 6

   C. 9

   D. 12

12. Which BEST describes the output of a shock- excited oscillator if R = 500 ohms and X L = 2,000 ohms?

   A. Underdamped

   B. Critically damped

   C. Overdamped

   D. Moderately damped

13. What will be the resulting action if R g is decreased (figure 4 of the text)?

A. Cutoff time increases

B. Conduction time decreases

C. Output frequency decreases

D. Output frequency increases

14. What type of feedback does a blocking oscillator employ?

A. Degenerative

B. Regenerative

C. In-phase

D. Out-of-phase

15. What is the formula for computing the Q in a parallel resistor tank circuit?

A. Q = XLxR

B. Q = XLxXC

C. Q = R/X L

D. Q = XC/X L

LESSON 4. MULTIVIBRATORS AND PHANTASTRONS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, function, and use of plate-coupled, one-shot, and Eccles-Jordan multivibrators and the basic phantastron.**
Lesson Credit Hours.....	**Three**

TEXT

1. GENERAL.

a. As explained in lesson 3, the blocking oscillator is a nonsinusoidal generator that generates voltage pulses of a short time duration for use as triggering pulses. Often, it is desirable to obtain rectangular voltage pulses of relatively long time duration (several hundred or thousand microseconds). A pulse of such long duration is used to gate circuits; i.e., to allow a circuit to conduct or be cut off for the duration of the pulse. A nonsinusoidal generator that will produce pulses of a long duration, either positive or negative polarity, is called a square wave generator (multivibrators).

b. There are various types of square wave generators, which you will encounter in your study of electronics. In this lesson, the three most common types of square wave generators, plate-coupled, one-shot and Eccles-Jordan multivibrators, are presented.

2. PLATE-COUPLED MULTIVIBRATOR.

a. General characteristics.

(1) The plate-coupled multivibrator is the simplest of these multivibrator circuits and, when properly designed, it can produce a waveshape that is almost perfectly square. In figure 1 note that basically the multivibrator consists of two triode amplifier stages, with the output of each stage introduced back into the input of the other. There are 360 degrees of phase inversion through the entire circuit. Therefore, feedback is in phase or regenerative, and the circuit will oscillate or free run. A slight change in the output of the first stage is fed to the input of the second stage. It is then amplified and fed back to the input of the first stage in phase with the original change.

(2) A plate-coupled multivibrator is called a relaxation-type oscillator; i.e., a tube alternately conducts for a period of time and then cuts off, or rests, for a time.

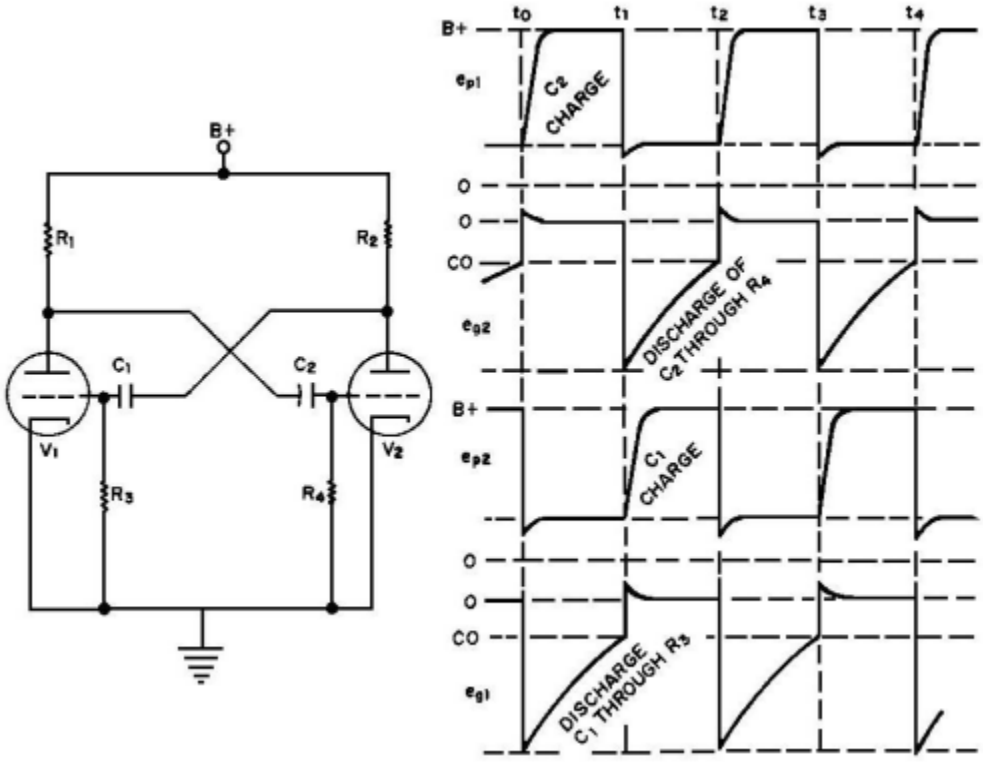


Figure 1. Plate-coupled multivibrator and waveshapes.

b. Circuit operation.

(1) When voltage is applied to the circuit, current flows through both tubes. The circuit is said to be symmetrical if all corresponding components (for both halves of the circuit) are equal, and if both tubes are of the same type. If the circuit is symmetrical, current flow should be the same through both tubes. Since it is impossible to obtain a perfectly symmetrical circuit, current flow will be greater through one tube than the other. Any slight change in current through one tube will start oscillations which produce the output waveshapes shown in figure 1.

(2) Prior to any change in tube current, the capacitors (C 1 and C 2) are charged to the plate-to-ground voltage of their respective tubes. Assuming that a slight increase in current has occurred through V 1, let us analyze the action with the aid of figure 2. As current increases through V 1, the voltage drop across R 1 will increase and the plate-to-ground voltage will decrease. Since C 2 is charged to the plate voltage of V 1, the decrease in the plate-to-ground voltage will cause C 2 to discharge to the new value. The discharge path of C 2 is denoted by the dotted line in figure 2. The discharge current flows through R 4 making the grid end negative. The negative grid of V 2 makes the current decrease through V 2, which causes a decrease in voltage drop across R 2. As the voltage across R 2 decreases, the plate-to-ground voltage increases. This rise in plate voltage will be instantaneously felt on the grid of V 1 (capacitor acts as a short at the first instant) causing the grid to draw current. Since C 1 is charged to the plate-to-ground voltage of V 2, it will now charge up to the new potential. C 1 has two charge paths: one through the resistor R 3, and the other through the cathode-to-grid resistance of the tube. These paths are indicated by the solid lines in figure 2. This current causes the top of R 3 and, therefore, the grid of V 1 to become more positive. This positive grid causes the original slight increase in current to become a tremendous current increase. As the changes go around the circuit a great voltage drop occurs at the plate of V 1, the voltage on the grid of V 2 becomes more negative, and the plate voltage of V 2 increases toward B+.

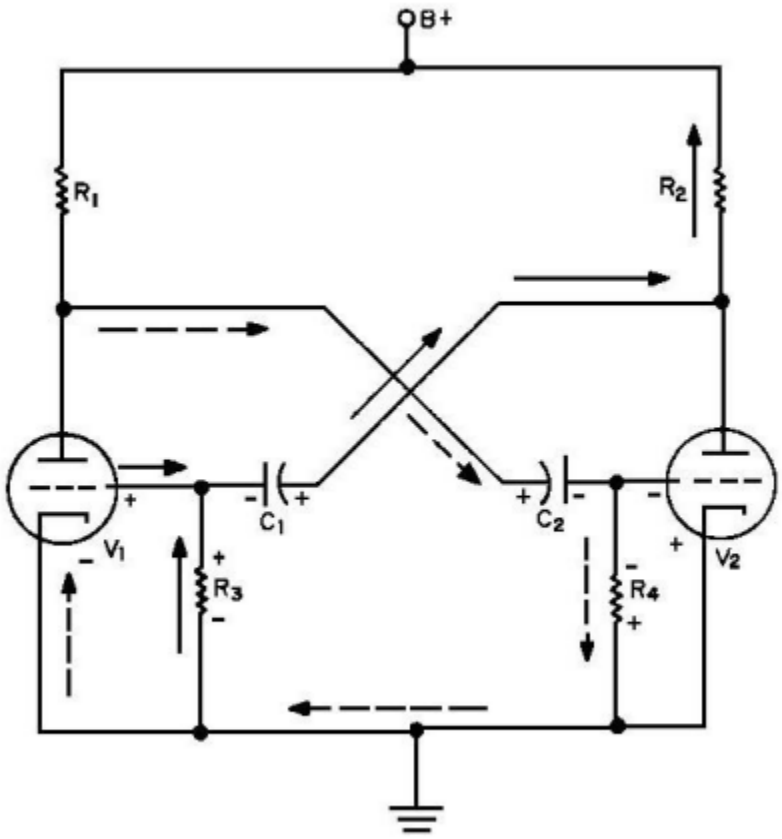


Figure 2. Action in circuits when V 1 conducts.

(3) This cumulative process continues until the current in V 2 is decreased to zero by a grid voltage far below cutoff. With zero current, the plate voltage of V 2 becomes equal to the plate supply voltage (B+) since there is no voltage drop across R 2. C 1 quickly charges to this value because of the grid current flow in V 1. The current through R 3 and the cathode-to-grid current become zero as soon as C 1 is fully charged. The plate voltage of V 1 remains at a constant low value for the duration of V 2 being cutoff. While C 2 is discharging the current (dotted line in figure 2) holds V 2 at cutoff. Everything remains at a standstill in the circuit, except for the slow discharge of C 2.

(4) The slow discharge of C 2 continues and the voltage across C 2 becomes lower and lower. The voltage drop across R 4 is rising toward cutoff potential (fig 1) as C 2 becomes more completely discharged. Upon reaching a voltage just greater than the cutoff voltage for V 2, a slight current starts flowing through V 2. This ends the period of conduction of V 1 and nonconduction of V 2.

(5) As current starts flowing through V 2 its plate voltage drops, due to the increased voltage drop across R 2. C 1, fully charged to B+, starts discharging in trying to follow the plate potential of V 2. As C 1 discharges (dotted line in figure 3) through R 3, the grid of V 1 becomes negative. The decrease in plate current of V 1, due to the negative-going grid, causes the plate voltage to rise. C 2 starts charging to the new plate potential of V 1, through R 4 and the cathode-to-grid resistance (solid lines in figure 3). This charging current makes the grid of V 2 more positive and the current through V 2 is increased tremendously. This regenerative process continues, with the grid of V 1 going negative and the grid of V 2 going more positive, until V 1 is cut off by the discharge of C 1 through R 3. At this point, V 1 plate voltage rises quickly to the plate supply voltage (B+) and, at the same time, the plate voltage of V 2 becomes steady at a low value.

(6) A second inactive period occurs as V 1 is held nonconducting by the slow discharge of C 1. The discharge continues until the voltage across R 3 is just above the cutoff potential of V 1 and V 1 starts conducting. The slight current in V 1 builds up in the same manner as described for V 2, until V 1 conducts heavily and V 2 is cut off.

c. Synchronization.

(1) Free-running multivibrators are generally not used in radar circuits because their frequency stability is poor. To avoid this, multivibrators are usually synchronized with an external frequency. The external frequency forces the period of the multivibrator oscillation to be exactly the same as the period of the synchronizing frequency. Such a multivibrator is said to be driven by the synchronizing voltage. For proper synchronization, the frequency of the external trigger must be slightly greater than the natural free-running frequency of the multivibrator.

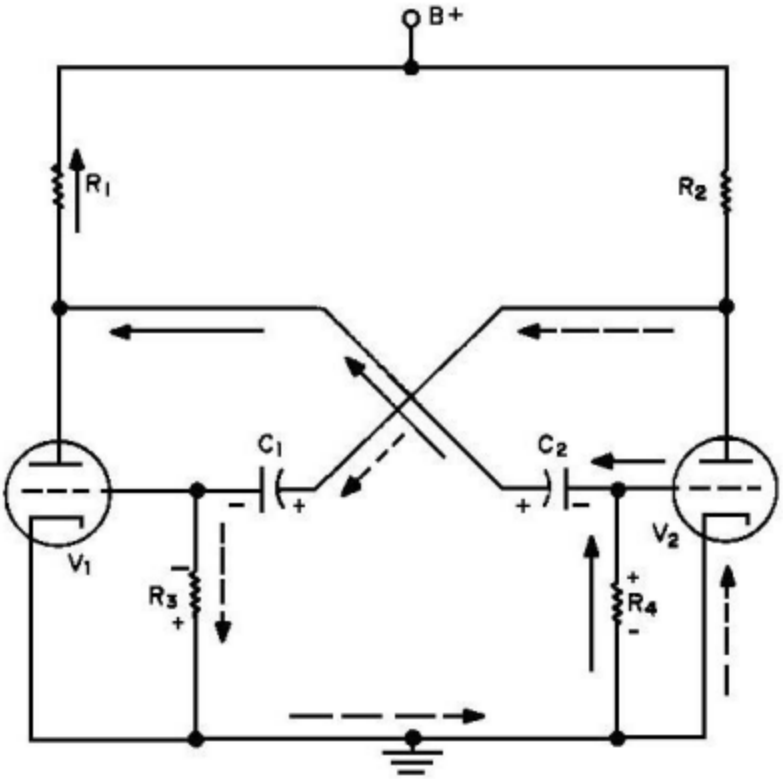


Figure 3. Action in circuits when V 2 conducts.

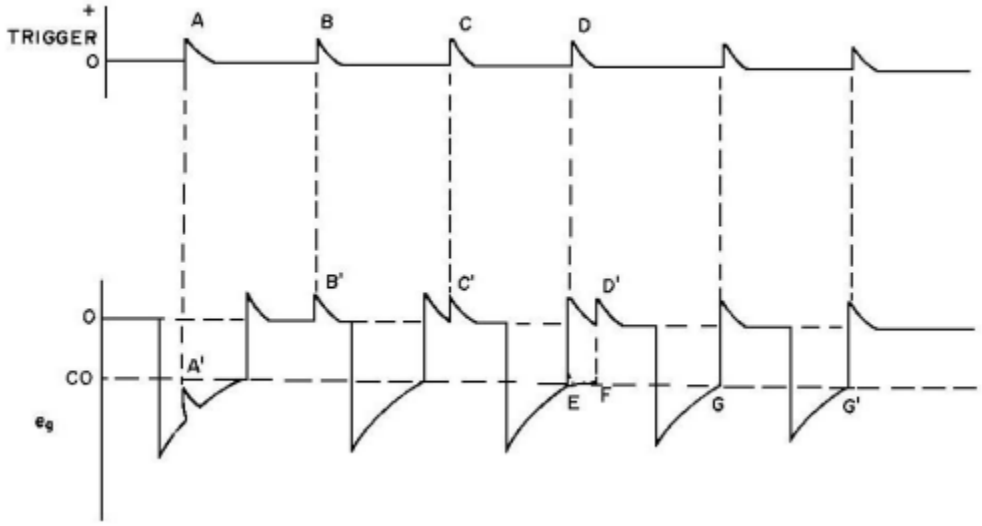


Figure 4. Synchronization with positive pulses on grid.

(2) Although multivibrators can be synchronized with a sine wave voltage, a more satisfactory method is obtained by the use of short trigger pulses. These pulses may be either positive or negative. In figure 4, note the effect of positive pulses on the multivibrator grid waveform. A positive pulse such as at B or C, when applied to a tube that is already conducting, causes a momentary increase in current flow. Thus, a positive trigger pulse applied to a conducting tube has practically no effect on the action of the multivibrator. However, when a positive trigger pulse is applied to a nonconducting tube and is of sufficient amplitude to raise the grid above cutoff (as the pulse at D), the tubes are switched as current starts to flow in the tube that was formerly cut off. Therefore, a positive trigger pulse applied to a nonconducting tube can cause switching action to take place only if the pulse is large enough to raise the grid above the cutoff voltage.

3. ONE-SHOT MULTIVIBRATORS.

a. General characteristics.

(1) The one-shot multivibrator, commonly referred to as a start-stop multivibrator, is one of the most widely used MVB circuits in electronics. It is a triggered device requiring an external input pulse for each cycle of output. Like the plate-coupled-type, the one-shot multivibrator is also called a relaxation type oscillator: i.e., a tube will alternately conduct and cut off, or rest, for a period of time.

(2) In figure 5, we see that the circuit consists essentially of a two-stage, resistance-capacitance-coupled amplifier with one tube normally cut off and the other conducting. The circuit has a monostable condition with V 1 cut off and V 2 conducting. The balanced condition of the circuit is established by the biasing arrangement of the tubes. The grid of V 2 is connected to its cathode through the resistor R 2. The cathode of V 2 is connected to the cathode of V 1.

b. Circuit operation.

(1) When voltage is applied to the circuit, current flows through R k and to the tubes. The positive voltage drop across R k will be felt on the cathode of V 1, cutting V 1 off. Since V 1 is cut off, its plate voltage will be at B+ and the capacitor (C 2) will try to charge to this value. C 2 has two charge paths; one through R 2, and the other through the cathode-to-grid resistance of V 2. As C 2 charges toward the plate potential of V 1, the grid of V 2 becomes positive, thus, overcoming the positive bias developed across R k. As soon as C 2 is fully charged, there is no more current flowing through R 2. With no current flow, R 2 acts as a short and the grid and cathode of V 2 are at the same potential. At this time, the circuit is in its stable condition with V 1 cut off and V 2 conducting. V 1 is cut off by the fixed bias and V 2 is conducting with zero volts bias.

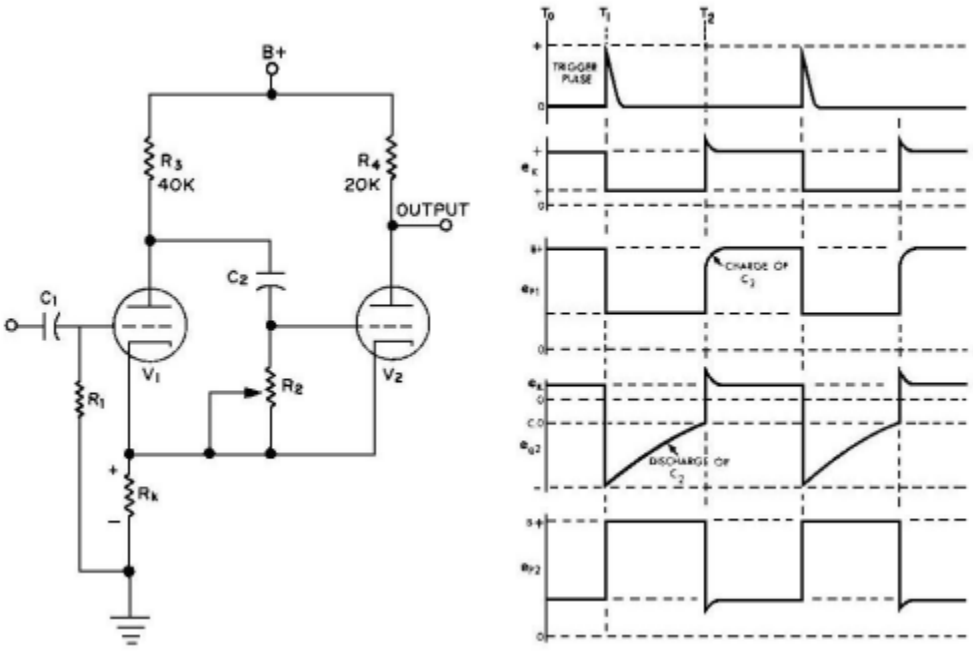


Figure 5. One-shot multivibrator and waveshapes.

(2) The circuit will remain in this stable condition until an external trigger pulse is applied. At time T 1 (fig 5), a positive trigger is applied to the grid of V 1. This positive trigger is of sufficient amplitude to overcome the fixed bias on the cathode of V 1 and to allow it to conduct. As V 1 starts conducting, the voltage drop across R 3 increases and the plate-to-ground voltage decreases. C 2 acts as an instantaneous short and the negative-going plate voltage of V 1 is felt on the grid of V 2, cutting V 2 off. After the first instant C 2 starts discharging toward the new plate potential of V 1. The discharge path of C 2 is from the bottom plate, through R 2, cathode-to-plate of V 1, and back to the upper plate. The circuit is now in an unstable condition with V 1 conducting and V 2 cut off. The circuit will remain in this condition only until the negative grid voltage on V 2 rises above the cutoff potential of the tube. When this occurs (time T 2, fig 5) V 2 will conduct and V 1 will cut off, due to the fixed bias of R k.

(3) Notice in figure 5 that the width of the trigger pulse is quite narrow and that it could not sustain conduction of V 1 for the full period between T 1 and T 2. However, the size of the plate-load resistors (R 3 and R 4) is such that when V 1 conducts, the voltage drop across R k is not sufficient to cut V 1 off. During this alternation, V 1 is conducting with a cathode self-bias and V 2 is cut off with the grid-leak bias. The cutoff time of V 2 is controlled by the size of C 2, R 2, and R 3. C 2 and R 2 determine the time constant and R 3 determines the plate swing of V 1, or the amount of voltage that C 2 will discharge. Therefore, the length of the output pulses produced is mainly controlled by the time constant of R 2 and C 2.

(4) In figure 5 each positive input trigger pulse, which causes V 1 to conduct, results in a large positive-pulse output from the plate circuit of V 2. The length of this positive output pulse is controlled by the time constant of R 2 and C 2. If a larger value of these components is used, the length of the positive output is increased. A positive output square wave is produced for each positive-input trigger pulse.

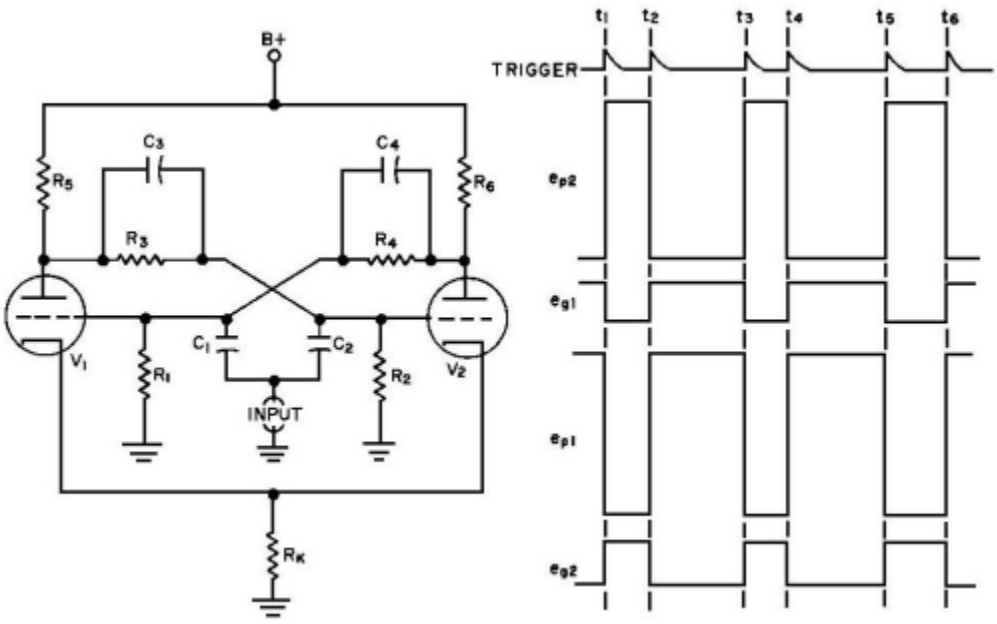


Figure 6. Eccles-Jordan multivibrator and waveshapes.

4. ECCLES-JORDAN MULTIVIBRATOR.

a. General characteristics.

(1) The Eccles-Jordan multivibrator, sometimes called a flip-flop multivibrator, is one of the most stable circuits used in electronics. It is a triggered device requiring two input triggers for one cycle of output. Since the Eccles-Jordan has such a stable output it is very often used to gate circuits where a high degree of accuracy is required.

(2) The Eccles-Jordan multivibrator is a bistable oscillator; i.e., it has two stable conditions: V 1 conducting and V 2 cut off, and V 2 conducting and V 1 cut off. Initially, the circuit can go into either one of the two conditions and will remain in such condition until an external trigger is applied. Therefore, the circuit has an input-to-output ratio of 2:1.

(3) The input trigger pulses may be applied to the grids, cathodes, or plates of the tubes and may be either positive or negative in polarity. Since this circuit will not switch, or flip, without an input trigger, the time between trigger pulses will determine the time duration (width) of the resulting rectangular or square wave produced by the multivibrator. Therefore, the frequency of the input triggers determines both the output frequency and the time duration of each alternation.

b. Circuit operation.

(1) In figure 6 when power is applied, and no trigger pulses are injected, current begins flowing from ground to B+. Normally, the Eccles-Jordan multivibrator is constructed symmetrically (corresponding components equal) to give a good square wave output. As current starts flowing, the plate voltage of one tube will drop faster than that of the other. Notice that the plate of each tube is resistively (directly) coupled to the control grid of the other tube. The speedup capacitors (C 3 and C 4) act as shorts to any instantaneous change in plate voltage. Assuming that V 2 conducts harder than V 1, its plate voltage will drop faster. The capacitor (C 4) will act as a short (shorting out R 4) and the entire negative-going voltage developed across R 1 will be felt on the grid of V 1, causing it to conduct less. The plate-to-ground voltage of V 1 will increase (since the voltage across R 5 decreases) and will be coupled through C 3 and R 2. The positive-going voltage on R 2 will cause V 2 to conduct harder and its plate voltage to decrease more. The negative-going plate voltage of V 2 will be coupled to the grid of V 1, which will cause V 1 to conduct less. This action is cumulative until V 2 is conducting hard and V 1 is cut off. The circuit is now in one of its two stable conditions and will remain as such until an external trigger is applied.

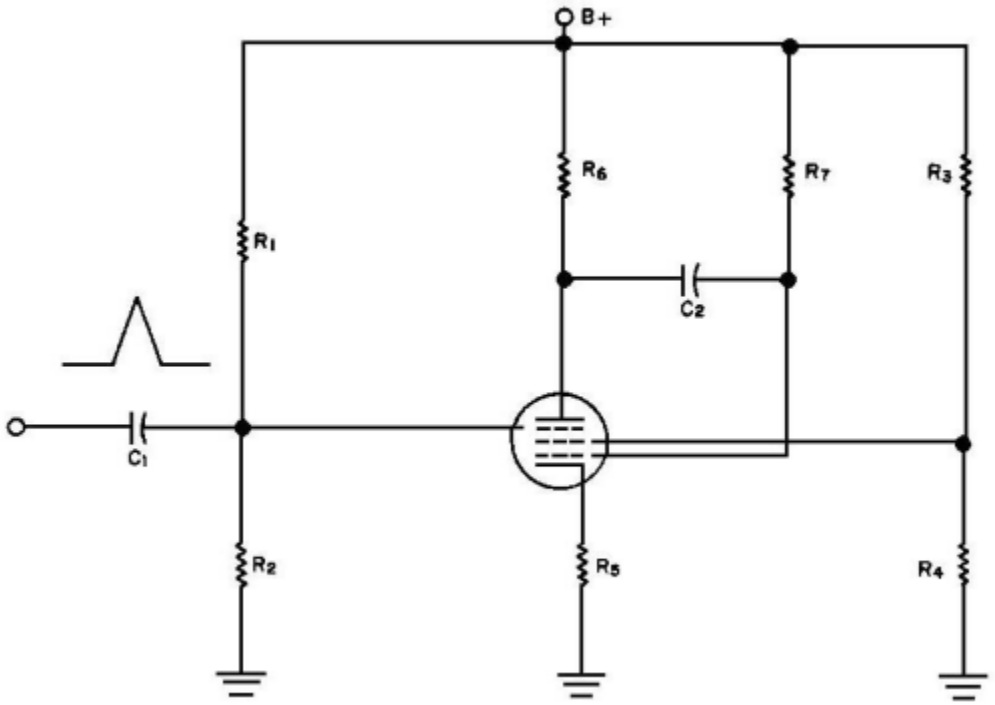


Figure 7. Basic phantastron circuit.

(2) Although any polarity can be used as a trigger, we will use positive pulses as indicated by figure 6. At time T 1 the first positive pulse is applied to the input and coupled through C 1 and C 2 to both grids. The pulse has practically no effect on V 2 since it is already conducting very heavily; however, when the positive pulse is applied to the grid of V 1, this tube will start conducting. As the plate current increases through V 1, the plate-to-ground voltage will decrease. Since C 3 acts as a short to instantaneous voltage changes, R 3 is shorted out and all of the negative-going plate voltages will be felt across R 2. This negative voltage, along with the bias voltage from R k, will cut V 2 off and its plate voltage will rise toward B+. The positive-going plate voltage is then coupled through C 4 to the grid of V 1, causing V 1 to conduct very hard. Due to the use of the speedup capacitors (C 3 and C 4), the switching, or flip-flop, action will be instantaneous and not cumulative.

(3) The circuit will remain in the condition of V 2 being cut off and V 1 conducting (time T 1 - T 2, fig 6) until another trigger pulse is applied. At time T 2 another trigger pulse is applied to the grids of V 1 and V 2. This positive pulse will cause V 2 to start; conducting and its plate voltage to drop. The negative-going plate voltage will be coupled through C 4 to the grid of V 1, cutting V 1 off. Therefore, from time T 2 to T 3 (fig 6) V 1 is cut off and V 2 is conducting.

(4) An output can be taken from the plate of either tube, and the waveshapes will be of the same duration. Since the circuit will produce a square or rectangular wave only when it is triggered by two external pulses, both the output frequency and the width of the individual alternations are controlled by the frequency of the trigger pulses.

5. PHANTASTRONS.

a. In radar, the range of a target is determined by measuring the time interval between the transmitted pulse and the received echo. A useful circuit for obtaining a controllable time delay for timing purposes is the phantastron. In operation, the phantastron is similar to a multivibrator. Its usefulness, however, lies in the fact that its pulse duration is a direct function of a control voltage obtained by some type of variable resistor. This control by a DC voltage makes remote control feasible at any distance by means of unshielded power cables since there is no signal present.

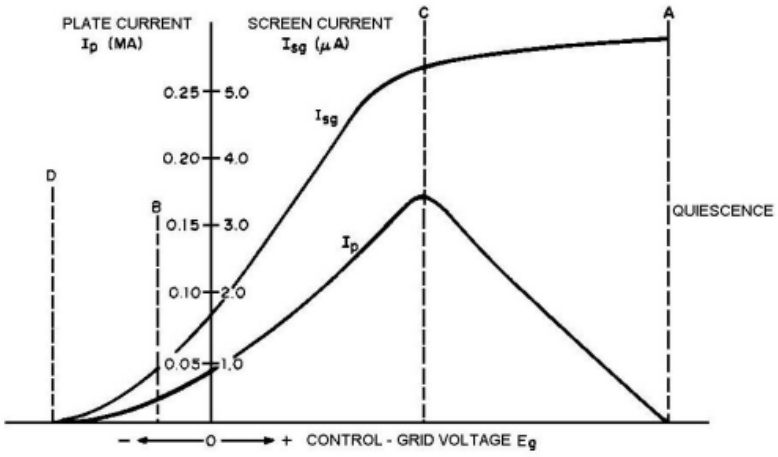


Figure 8. Phantastron circuit characteristics.

b. The phantastron is said to be a stable circuit because when power supply voltages change it remains stable. Its operation depends on the fact that there is a specific DC voltage relationship between the tube elements. Any variation of source voltage varies all of these voltages in the same proportion, thus, causing a minimum change in the voltage relationship.

6. CIRCUIT CHARACTERISTICS.

a. A phantastron of the type requiring an external triggering pulse is shown in figure 7. This circuit employs a pentode with the capacitor (C 2) providing feedback from the plate to the control grid. The tube has a sharp suppressor grid-to-plate cutoff that enables both the control and suppressor grid to control the tube current. The control grid determines the total space current, which is the sum of the plate and screen grid currents, and the suppressor grid controls the division of current between the plate and the screen grid. The characteristics and voltage waveforms of the circuit are shown in figures 8 and 9. Note in figure 8 that the screen grid current seems to be much greater than the plate current, however these currents are plotted to different scales.

b. The relationship between R 1 and R 2 is such that the suppressor grid is held only a few volts positive with respect to ground. The relationship of R 3 and R 4 is such that the screen grid is always positive with respect to the cathode.

c. Figure 8 shows that if the control grid is made sufficiently negative, both plate and screen currents may be cut off (point D). As the control-grid voltage is made more positive, both of these currents increase and raise the potential of the cathode. Since the suppressor is held at a small DC potential, it becomes more negative with respect to the cathode. As a result, a smaller fraction of space current reaches the plate until, at point C, the plate current begins to decrease. This continues until the suppressor potential is sufficiently negative, with respect to the cathode, to reduce the plate current to zero. Note on the characteristic curve, that from point C to point A, the plate current decreases even though the control grid continues to increase. At point A the control-grid potential is slightly more positive than the cathode and control-grid current flows.

d. In figure 7 the following two quiescent conditions can be determined: the grid current flows to put the control grid close to the potential of the cathode, and the control-grid current charges C 2 to the difference of potential between the plate and the control grid (E p - E g). The charge path is from the plate of C 2 through R 6, B+, ground, R 5, cathode, and grid to the other plate of C 2. With the control grid returned to a high positive potential the total space current through the tube is high. This makes the cathode sufficiently positive with respect to the suppressor grid to cut off the plate current. With a large space current flowing through the tube, and with no plate-current flow, a large screen-grid current must be flowing. Since the above conditions of operation occur before the application of an external trigger, point A of figure 8 is the quiescent operating point.

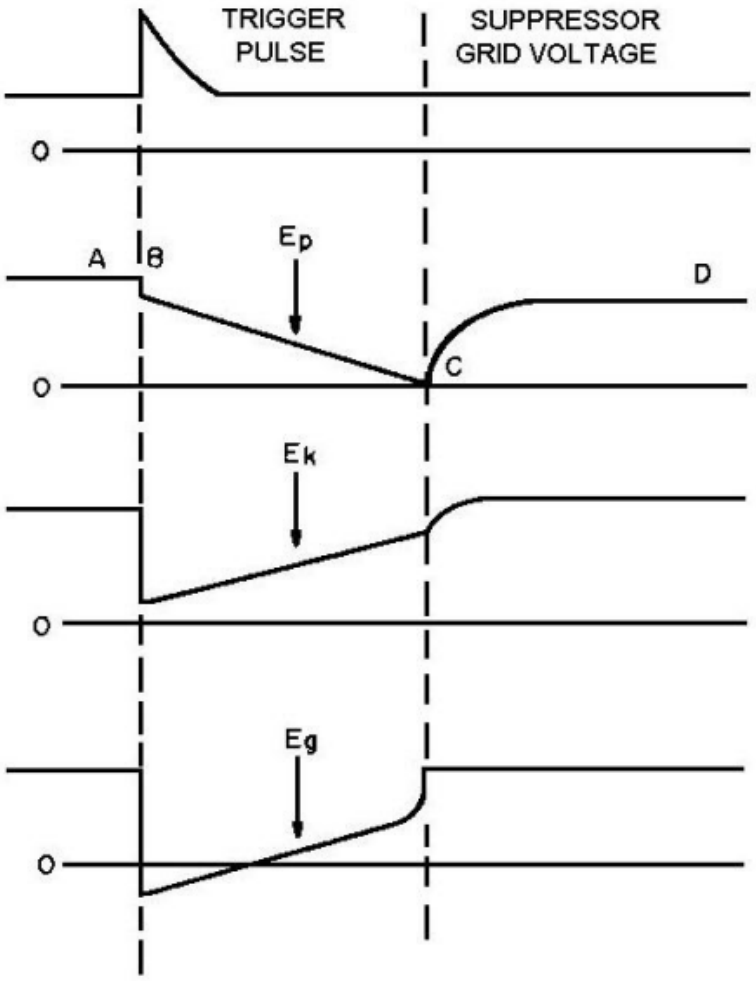


Figure 9. Phantastron - waveforms.

7. CIRCUIT OPERATION.

a. The circuit (fig 7) is triggered by a positive pulse coupled through C 1 to the suppressor grid. This raises the suppressor grid above the plate circuit cutoff and the plate current flows instantaneously. Figure 8 shows that, at this time, the plate current increases and the screen grid current decreases with the net result that the total space current is decreased. As a result of the decreased space current, the cathode potential is no longer positive enough for the suppressor to hold the plate at cutoff. Thus, the plate continues to draw current even after the trigger pulse has expired. The initial switching action ends at point B on the curve of figure 8.

b. As soon as an external trigger is applied and the plate starts drawing current (point B, fig 9), the plate-to-ground voltage decreases. C 2 (fig 7) acts as an instantaneous short to this voltage change and then starts discharging through R 7 to the new voltage potential of the plate. After the initial switching action, the control-grid voltage begins to rise as the charge across C 2 decreases. The rise in control-grid voltage causes the plate current to increase and the plate voltage to decrease. This decrease increases the amount of voltage discharged by C 2 and, hence, counteracts the original rise in the control-grid voltage. The result is that, following the initial switching action, the discharge of C 2 tends to follow a linear path rather than the normal exponential curve.

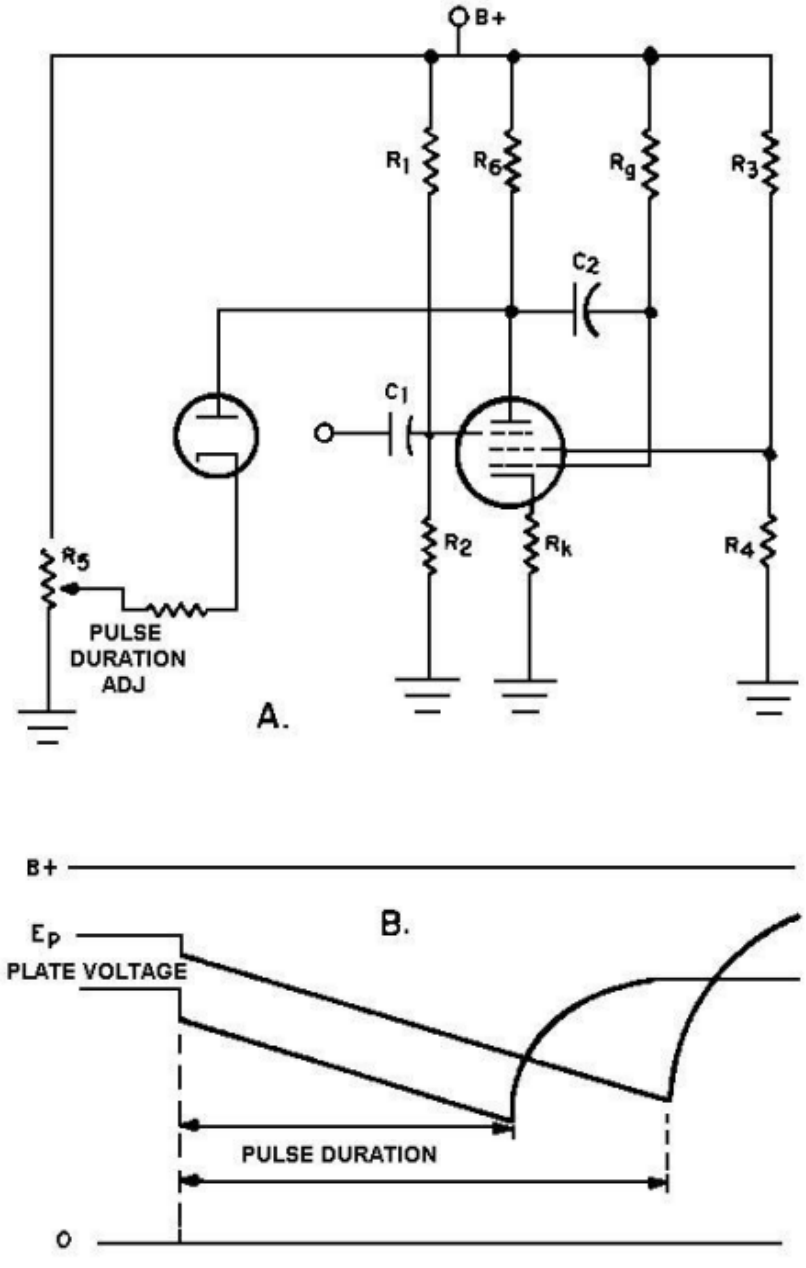


Figure 10. Phantastron - circuit and waveforms.

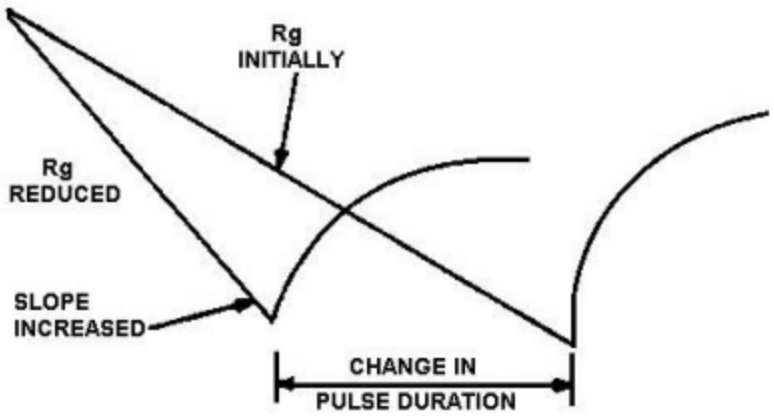


Figure 11. Plate waveforms showing effect of changing R g.

c. The degenerative effect of C 2 causes the circuit operating point to move slowly from point B to the right, as illustrated in figure 8. As the capacitor slowly discharges, the control-grid voltage rises linearly toward the plate-current cutoff point at C in figure 9. When point C is reached in figures 8 and 9, the cathode voltage has risen to a point where the suppressor grid is negative, with respect to the cathode, and the plate current starts decreasing. This results in an increasing voltage at the plate, which is coupled through C 2 to the control grid as a positive voltage. The regenerative effect causes a sudden rise in the cathode voltage. As the cathode potential becomes increasingly positive, the circuit is rapidly driven into its quiescent condition at point A of figure 8.

8. PRACTICAL PHANTASTRON CIRCUITS.

a. A phantastron is used to provide a variable time delay by changing the pulse width. Satisfactory phantastron pulse variation is achieved by changing the plate voltage of the tube (A, fig 10). The diode conducts when the voltage at the phantastron plate slightly exceeds the voltage placed on the diode cathode by R 5. Therefore, during quiescence, the diode will limit the voltage at the phantastron plate to approximately that value set in by R 5. The voltage to which C 2 charges during quiescence is determined by this plate voltage. Since the discharge of C 2 is essentially linear when the circuit is triggered, and since a change in plate voltage does not alter the control-grid voltage at point C (fig 9), the duration of the pulse is directly proportional to the setting of R 5. The effect of changing R 5 is shown by the waveforms in B, figure 10.

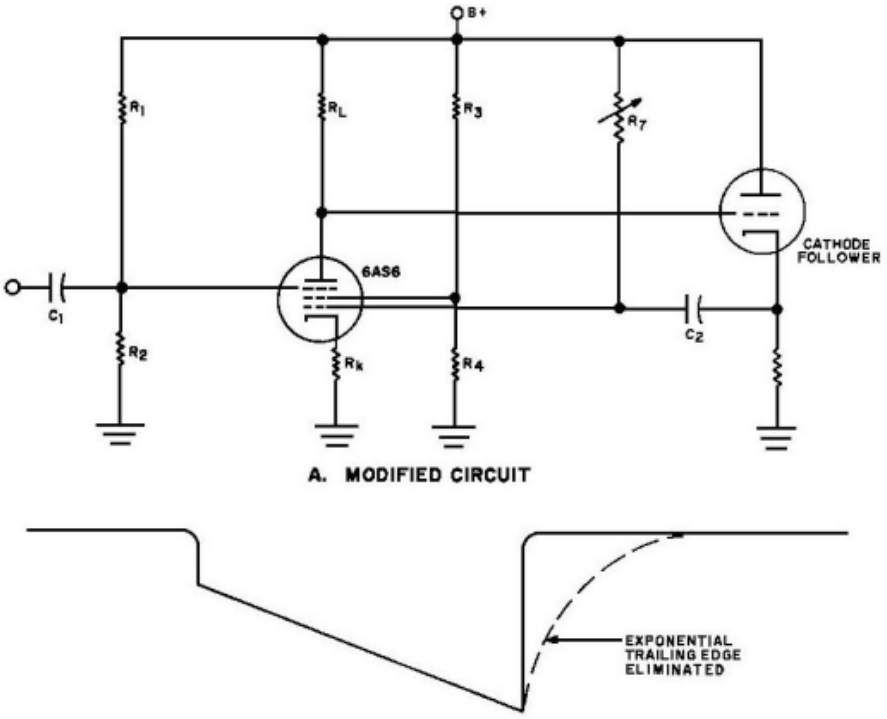


Figure 12. Circuit for reducing phantastron recovery time.

b. Sometimes it is necessary to change the slope of the output waveform. This can be done by changing the value of R 7 (fig 12) that is in the discharge path of capacitor C 2. The effect of reducing the value of R 7 is shown in figure 11. The pulse duration is also altered when the slope is changed.

c. To make portion B-C (fig 9) of the output wave linear, resistor R 6 must have a high value in order that the change in plate voltage be large as compared to the change in grid voltage. This large value of R 6 creates a long, exponential, charging curve on the output wave by increasing the time constant of the charging circuit for C 2. To reduce this charging time to a more reasonable value, a cathode follower is inserted in the plate-to-grid feedback circuit (A, fig 12). The cathode follower provides a low impedance charge path for C 2, thereby decreasing charge time and making the lagging edge of the waveform fairly linear (B, fig 12).

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 4

1. What is a characteristic of the plate-coupled multivibrator?

   A. It has exceptional frequency stability

   B. It has good frequency stability

   C. It produces a sine wave output

   D. It produces a square wave output

2. What is the result if R 4 is increased in figure 1?

   A. Output frequency increases

   B. Cutoff time of V 1 increases

   C. Conduction time of V 1 increases

   D. Conduction time of V 2 decreases

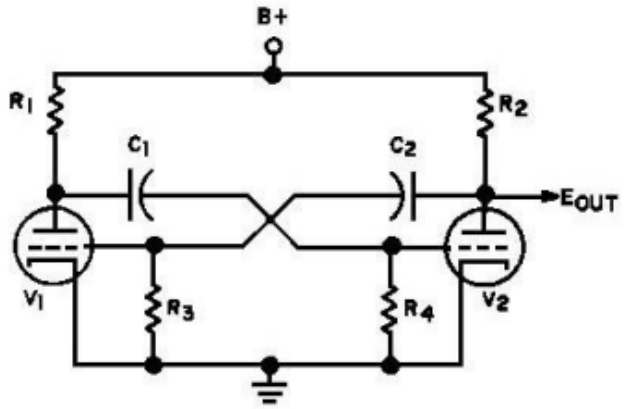


Figure 1.

3. What action results if R 2 is decreased in figure 1?

   A. Output frequency increases

   B. Output frequency decreases

   C. Cutoff time of V 2 decreases

   D. Cutoff time of V 1 increases

4. What type pulses are normally used as the synchronizing trigger for a plate-coupled multivibrator?

   A. Negative pulses at a frequency two times the natural frequency of the multivibrator

   B. Positive or negative pulses at a frequency slightly greater than the natural frequency of the multivibrator

   C. Positive or negative pulses at a frequency slightly less than the natural frequency of the multivibrator

   D. Positive pulses at a frequency two times the natural frequency of the multivibrator

5. What happens if an external synchronizing trigger is applied to the circuit in figure 1?

   A. Output frequency increases

   B. Duration of each square wave increases

   C. Output frequency decreases

   D. Amplitude of square wave output decreases

6. What happens if C 2 is decreased in figure 1?

   A. Cutoff time of V 2 decreases

   B. Output amplitude decreases

   C. Cutoff time of V 1 increases

   D. Conduction time of V 2 decreases

7. What is a characteristic of the one-shot multivibrator?

   A. It requires one input trigger for one alternation of output

   B. It has bistable condition

   C. It requires one input trigger for one cycle of output

   D. It has tristable conduction

8. What type bias is used to stop conduction in V 1 of figure 2?

   A. Fixed

   B. Cathode-self

   C. Grid leak

   D. Variable

9. What determines the duration of the negative gate output of V 2 in figure 2?

   A. Size of R 3

   B. Frequency of the input trigger

   C. Size of R 1

   D. Amplitude of the input trigger

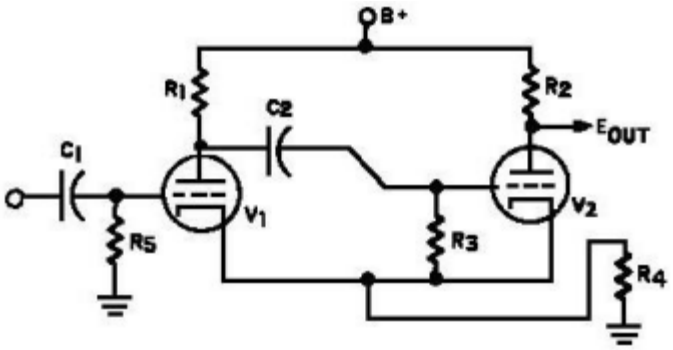


Figure 2.

10. In figure 2, how will increasing the size of R 2 affect circuit operation?

    A. Conduction of V 2 will increase

    B. Amplitude of the output will increase

    C. Conduction of V 1 will decrease

    D. Output frequency will decrease

11. What BEST describes the operation of the Eccles-Jordan multivibrator?

    A. It is either free-running or triggered

    B. It is either monostable or bistable

    C. It needs one input trigger for one cycle of output

    D. It needs two input triggers for one cycle of output

12. What is (are) the stable condition(s) of the Eccles-Jordan multivibrator?

    A. V 1B conducting and V 2A cut off

    B. V 2B conducting and V 1A cut off

    C. V 1 conducting and V 2 cut off; V 2 conducting and V 1 cut off

    D. V 1A conducting and V 2B conducting; V 2A cut off and V 1B cut off

13. What determines the output frequency of the circuit in figure 3?

A. The input trigger frequency

B. The time constants of C 1, C 2, R 5, and R 6

C. The time constants of C 3, C 4, R 5, and R 6

D. The input bias frequency

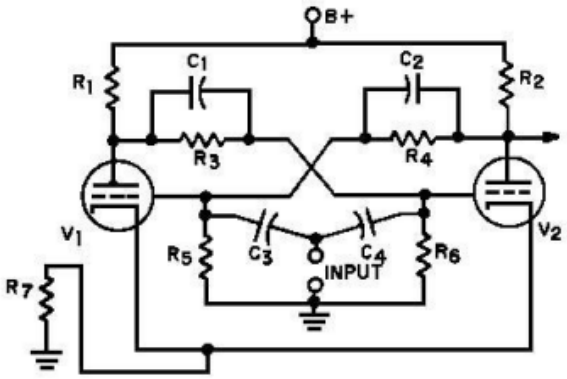


Figure 3.

14. What controls the amplitude of the multivibrator output in figure 3?

A. R 6

B. R 5

C. R 2

D. R 1

15. In which circuit is the output pulse duration a direct function of the control voltage?

A. Phantastron

B. Plate-coupled multivibrator

C. Cathode-coupled multivibrator

D. Shock excited oscillator

16. In figure 4, what happens in the circuit if capacitor C 1 is increased?

A. The frequency decreases and the duration decreases

B. The frequency increases and the duration decreases

C. The slope increases and the duration increases

D. The slope decreases and the duration increases

17. How will readjusting R 8 upward affect the circuit in figure 4?

A. The output duration will decrease

B. The output duration will increase

C. The output frequency will increase

D. The output frequency will decrease

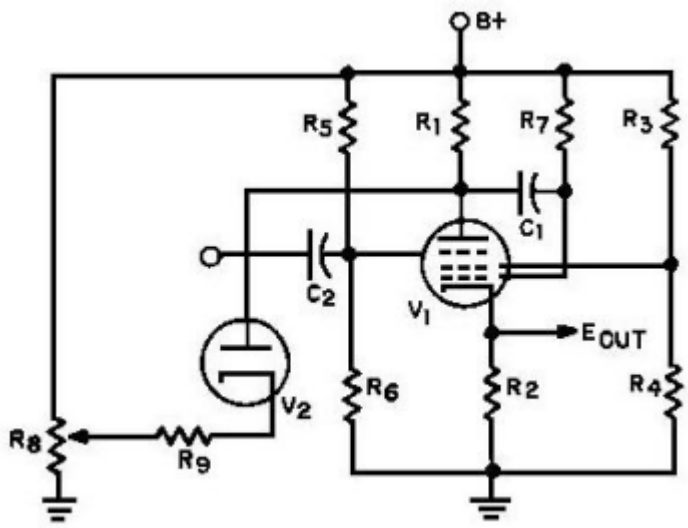


Figure 4.

18. What is ONE of the quiescent conditions of a phantastron?

A. Plate slightly negative with respect to the cathode

B. Suppressor grid negative with respect to the cathode

C. Control grid negative with respect to the cathode

D. Screen grid slightly positive with respect to the cathode

19. What is (are) the stable condition(s) of the one-shot multivibrator in figure 2?

A. V 2 cut off and V 1 conducting

B. V 1A and V 2A cut off; V 1B and V 2B conducting

C. V 1A cut off and V 2A conducting; V 2B cut off and V 1B conducting

D. V 1 cut off and V 2 conducting

20. What is the purpose of speedup capacitors C 1 and C 2 in figure 3?

A. To determine the output amplitude

B. To determine the output frequency

C. To maintain a constant square wave output

D. To maintain a constant sinusoidal wave output

LESSON 5. SWEEP GENERATORS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, function, and use of basic sweep generator circuits used to produce sweep voltages; to include electrostatic and electromagnetic deflection and methods of improving the linearity of the sweep generator outputs.**
Lesson Credit Hours.....	**Two**

TEXT

1. GENERAL.

a. A sweep generator, commonly called a time-base generator, is a circuit that generates the voltage or current, which causes an electron beam to move across a cathode ray tube (CRT) screen at a constant rate. The distance along the trace formed by the moving beam is the basis for establishing time intervals. When recurrent voltage changes are super imposed on the trace, it is possible to measure both time and frequency of a radio signal and, in radar, to measure the distance of targets. General purpose test oscilloscopes usually employ a thyratron tube in the time-base generator circuit, because of the simple method by which the frequency can be changed. In radar sets, the time-base generator circuit usually employs a high vacuum tube.

b. Regardless of whether the CRT is electrostatic or electromagnetic, the time-base generator must meet certain requirements as follows:

(1) Provide sufficient voltage or current to cause the electron beam to move a predetermined distance across the screen.

(2) The electron beam must be made to move at a linear rate so that range measurements along the trace are linear. For example, if 1 inch of time base equals 5 miles, then 2 inches must be equal to 10 miles anywhere along the length.

(3) At the end of the trace the spot must return to the point of origin, and this return is known as the flyback.

c. To fulfill the above requirements in an electrostatic CRT, a sawtooth voltage may be applied to the deflection plates. In an electromagnetic CRT, a sawtooth wave of current must pass through the deflection coils. Thus, this lesson is devoted to the circuits, which produce sawtooth waveshapes.

2. THYRATRON SWEEP GENERATOR.

a. General characteristics.

(1) The movement of the spot in a CRT may be controlled either by a voltage change to the deflection plates or by a current change to the deflection coils. The chief requirement is that the voltage (or current) changes linearly with respect to time.

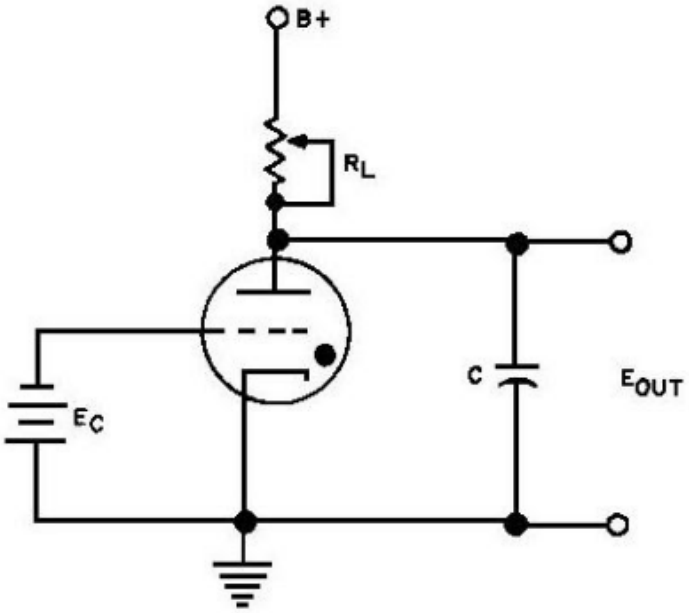


Figure 1. Thyratron sweep generator.

(2) Although both resistance-capacitive (RC) and inductive-resistance (LR) circuits consume time during a voltage change, the RC circuit is usually preferred and used. As previously studied in subcourse 704, if an RC circuit is connected to a DC voltage source, the capacitor will start to charge. Since the resistor limits the current, the charge will not be instantaneous but rather at an exponential rate. Since it is quite linear, only the first portion of the charging curve is usable in a sweep generator.

(3) Most time-base generators use a charging and discharging process by high-speed switching of the capacitor from charge to discharge. One device suitable for this high-speed switching is the gas tube or thyratron.

(4) As stated in subcourse 705, a thyratron is a gas-filled triode whose firing potential depends upon the value of the grid bias, and whose de-ionization potential is independent of grid voltage. Using a thyratron makes it possible to control the firing potential or amplitude of the sawtooth wave.

b. Circuit operation.

(1) Figure 1 is a schematic diagram of a thyratron sawtooth generator. For purposes of explanation let us assume that V 1 is a thyratron whose firing potential is 10 times its grid bias, and whose de-ionization potential is 15 volts. For a good linearity of the sweep, the sawtooth voltage should be in the first 10 percent of the capacitor's charge curve (10 percent of B+). Thus, if B+ is 500 volts the charge of the capacitor should be limited to 50 volts. When these constants are used in the circuit (B+ = 500v, E c = 5v) a fairly linear sawtooth output voltage is obtained.

(2) Referring to figure 1, when B+ is first applied C acts as an instantaneous short and the applied voltage is dropped across R L and, this time, the tube is an open circuit due to the negative voltage on the control grid. After the first instant the capacitor starts charging toward B+, at a rate determined by the size of R L and C, and will continue to charge until the firing potential of the thyratron is reached. Since the capacitor is in parallel with the plate-to-ground voltage (E out) of the tube, the voltage will rise at the same rate at which the capacitor charges (fig 2). As the voltage increases a potential is reached (E i, fig 2) where the voltage across the tube is so high that the negative voltage on the control grid cannot keep the tube cut off. As current starts flowing through the tube, a voltage is dropped across R L and the plate-to-ground voltage decreases. When the tube starts conducting, a discharge path is provided for C and the plate voltage drops at the same rate at which the capacitor discharges. The capacitor discharge path is from the bottom plate through the conducting tube to the upper plate. As the capacitor discharges and the plate voltage decreases, a point is reached (E d, fig 2) where the tube de-ionizes and the grid regains control of the circuit. At this point (de-ionization) the tube cuts off, acting like an open circuit, and the capacitor starts recharging toward B+.

c. Component variation.

(1) Referring to figure 2, the curve for several charges and discharges shows that the voltage increases to the ionizing potential (E i) and then drops very abruptly to the de-ionizing potential (E d). The slow rise is due to the size of R L and C. The rapid drop in voltage tries to form an RC curve, but the resistance of the ionized tube is so small that the capacitor is discharged almost immediately causing the curve to be practically vertical. The voltage at which ionization occurs depends on the amount of voltage applied to the grid. If the grid is made less negative, a lower plate voltage will ionize the tube (fig 2). When ionization occurs earlier, the amplitude of the wave shape will decrease but discharge time remains practically the same. Therefore, the wave will repeat more often; i.e., its frequency increases. Another noticeable result of lowering the ionization potential is increased linearity of the charging curve.

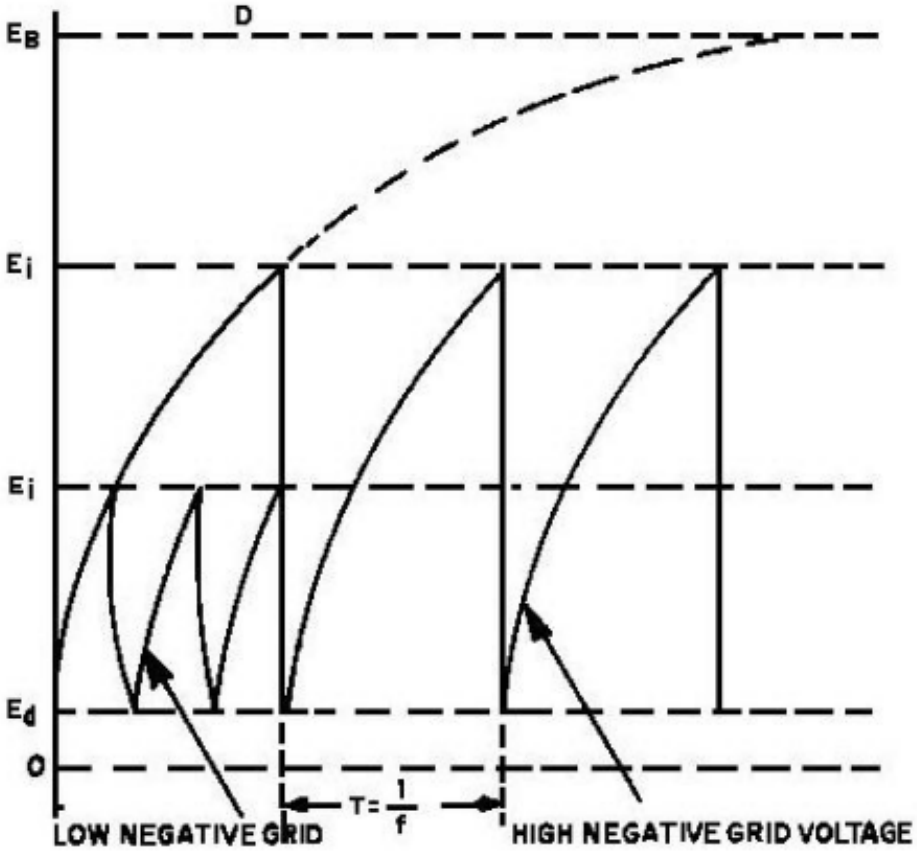


Figure 2. Thyratron sweep generator waveshapes.

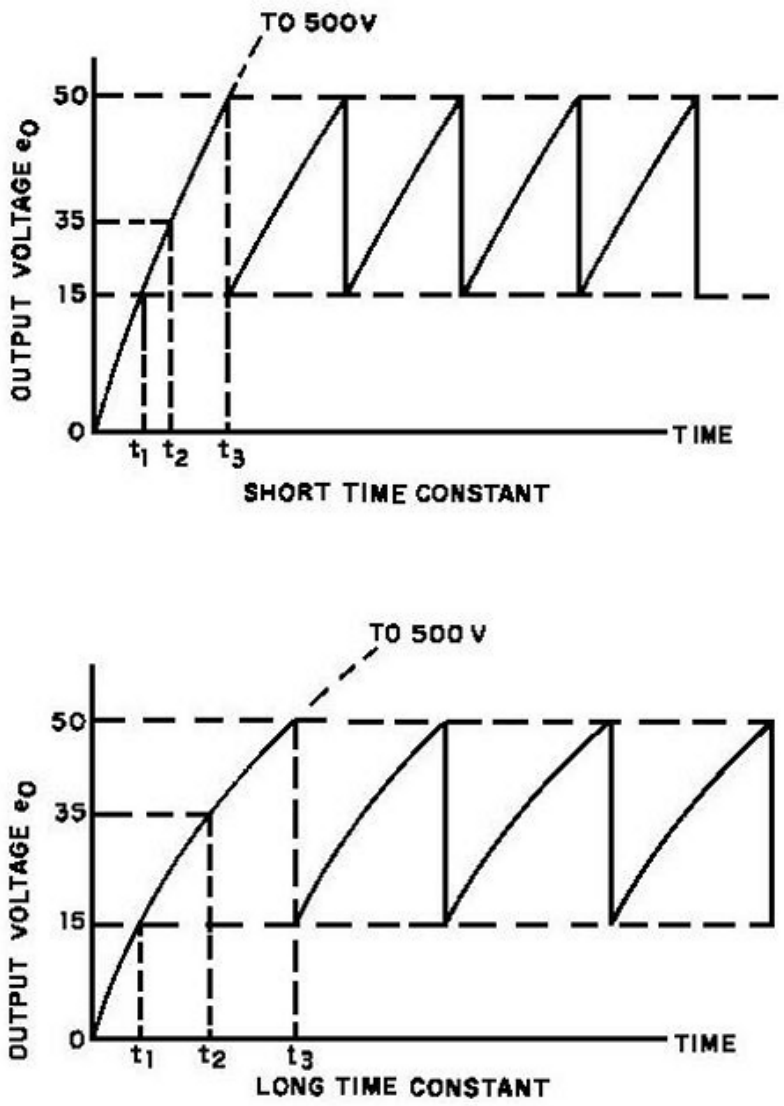


Figure 3. Output waveshape of a thyratron sawtooth generator.

(2) Since the time constant (R L x C) determines the time it takes for the voltage on the capacitor to reach the firing potential, it obviously controls the frequency of the generated sawtooth wave. In figure 3 the effect of both a short and long time constant on an output wave is illustrated, and it can be seen that as the time constant increases the frequency decreases. This conclusion may be reached if we recall that f = 1/T; where f is the frequency of a wave and T is the period of a wave. Since an increase in the time constant increases the time (period) of each wave, the frequency of the wave decreases. Note, however, that neither the amplitude nor the linearity of the sawtooth wave is influenced by a change in the time constant.

d. Synchronization.

(1) In addition to the factors just discussed the frequency is also affected by the temperature of the gas, the slightly variable ionization potential, and the load on the circuit. Because of these factors, the circuit is usually not stable enough to maintain an adequately constant frequency by itself. Rather, it must be synchronized by an external AC voltage that has a frequency near (usually a little above) the fundamental frequency of the thyratron generator. Due to the synchronization voltage, the thyratron tube ionizes slightly ahead of normal time and the capacitor discharges immediately starting a new cycle.

(2) Diagram A, figure 4, shows a typical synchronization circuit in which a sine wave is used to synchronize the sweep generator. The sine wave varies the grid voltage that controls the ionization potential. The waveshape at B, figure 4, shows how the ionization potential varies at a slightly higher frequency than the natural, free-running frequency of the generator. The dotted sawtooth waveshape results from a constant ionization potential. At the time the capacitor voltage is about to reach the normal value, the ionization potential drops. When the capacitor voltage reaches the ionization potential, ionization of the tube occurs and a new cycle begins immediately. The same action results with each cycle and causes the time-base frequency to lock-in with the synchronizing frequency.

(3) Often, as in the use of the oscilloscope, the waveshape being displayed on the CRT is used for synchronization. This is done so that the waveshape and time-base will occur simultaneously and the pattern will be stationary. If there is no synchronization, a difference in frequency will exist and the pattern displayed on the screen will move forward or backward along the time base.

3. HARD-TUBE SWEEP GENERATOR.

a. General characteristics.

(1) The frequency of a thyratron sawtooth generator is usually capable of meeting all the requirements of time-base generators used for cathode ray tubes in general purpose oscilloscopes. However, it is not readily adaptable to producing the time-base with the spaced intervals required by radar equipment. Therefore, a high vacuum or hard tube is used instead. A hard tube is one from which as much gas as possible has been removed. In contrast, a soft tube is one with an incomplete vacuum, which means that some gas is allowed to remain in the envelope.

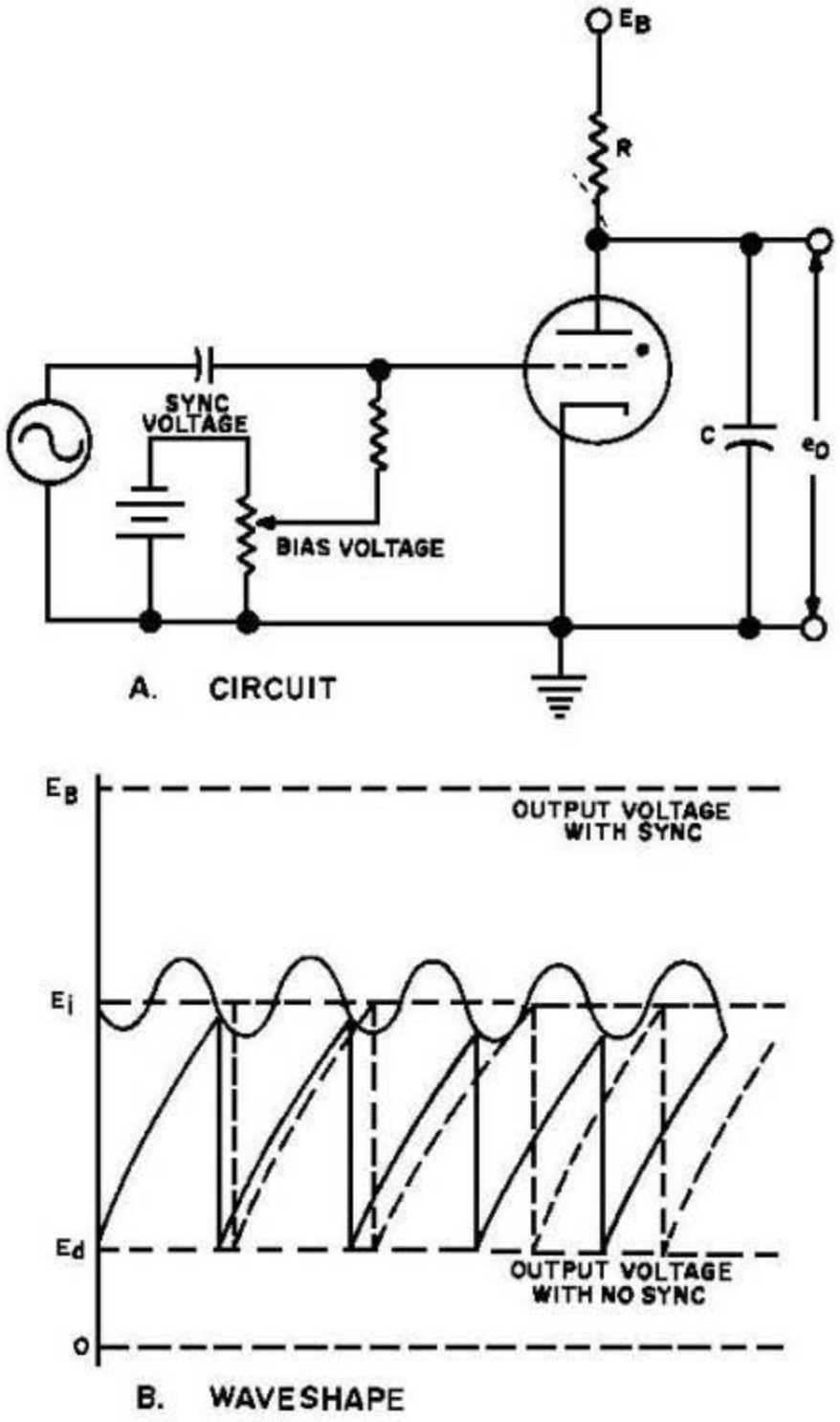


Figure 4. Synchronization with sine wave.

(2) The hard tube serves as a switch for discharging the capacitor, but is not automatic and must be operated by an external circuit. The external trigger is a negative-going square wave that, when applied to the grid, cuts off current flow.

b. Circuit operation.

(1) When B+ is applied to the circuit (fig 5), and zero volt is present on the grid, the tube conducts heavily. The external, input square wave will vary between zero volt (during which the tube conducts) and some negative value that will cut the tube off. Since the resistance of the tube is very low when conducting, most of the voltage will be dropped across R 2 and the plate-to-ground voltage will be quite low. Therefore, during conduction, the voltage that C 2 charges to will be the same as the low plate-to-ground value since they are in parallel. The current will remain in this state until a negative gate is applied.

(2) If the grid of V 1 is made sufficiently negative by the gate input E in (time T 1, fig 5), the tube will stop conducting and will act as an open circuit. Now, a series RC circuit consisting of B+, R 2, and C 2 is formed. As a result, C 2 begins to charge toward B+ at a rate determined by the time constant of R 2 and C 2. The charge of C 2 is shown from time T 1 to T 2 in figure 5. As indicated by the dotted line, C 2 would charge to B+ if the duration of the negative gate were long enough. However, at time T 2 the input gate rises to zero and V 1 starts conducting.

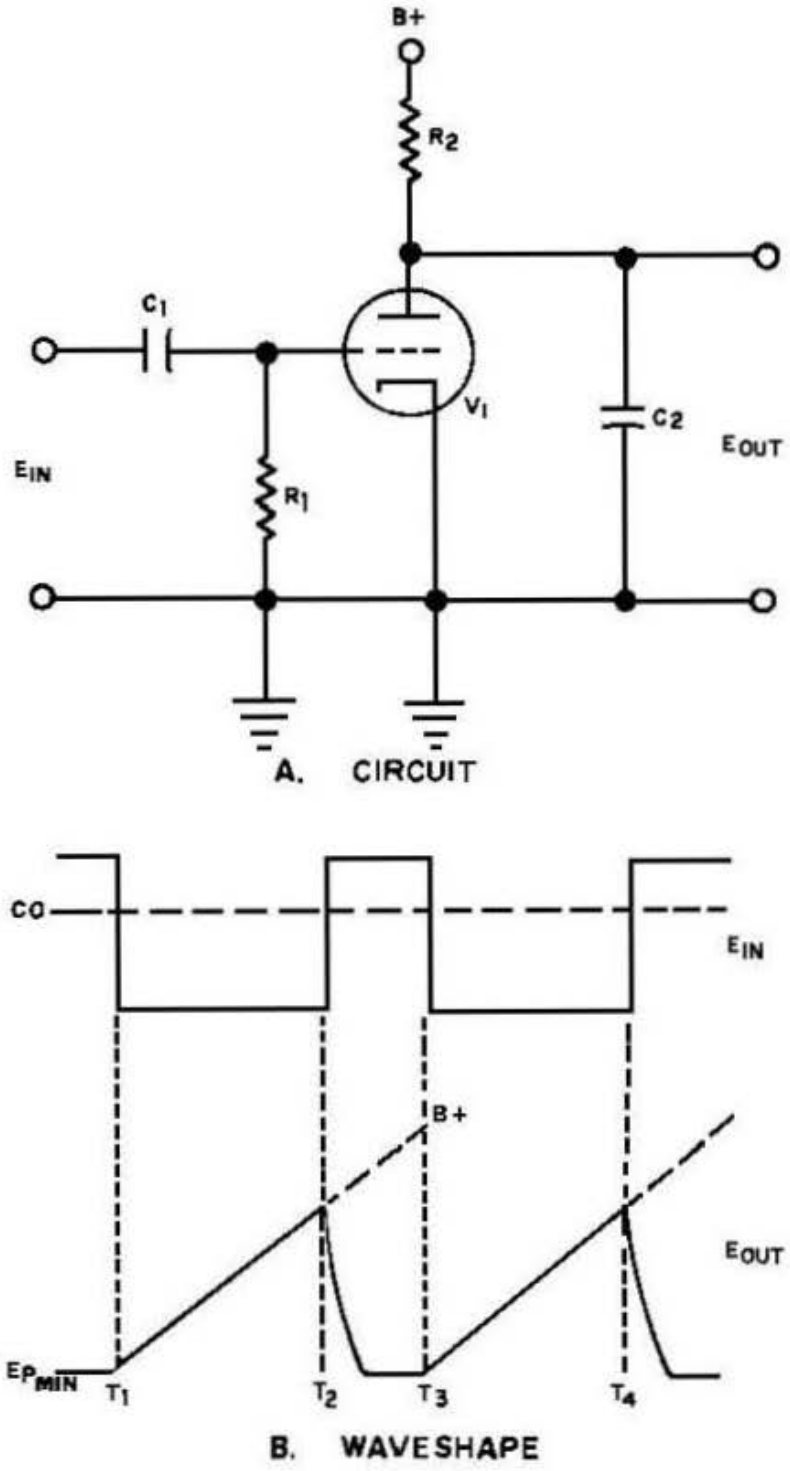


Figure 5. Hard-tube sweep generator and waveshapes.

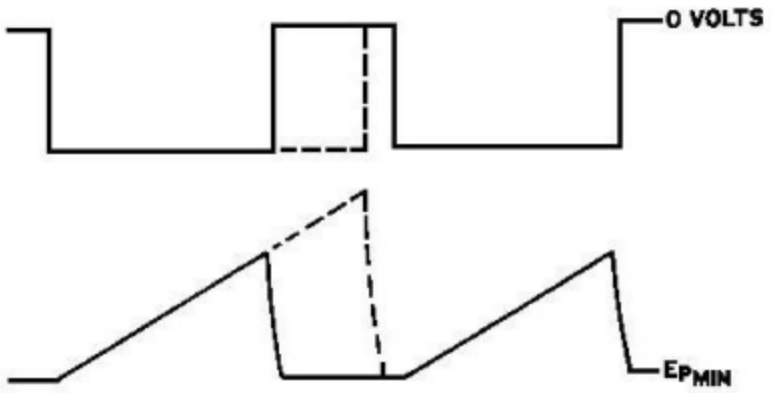


Figure 6. Hard-tube sweep generator waveshape variation.

(3) As V 1 again conducts, most of the applied voltage will be dropped across R 2 and the plate-to-ground voltage decreases. Since C 2 is connected in parallel with the plate-to-ground voltage of V 1, C 2 will discharge and the plate voltage will drop at a rate determined by the RC time constant of C 2 and the conducting tube. The discharge path of C 2 is from its bottom or negative plate, the cathode-to-plate of V 1, and back to its upper or positive plate. Since the resistance of the tube is fairly low, C 2 will discharge quite rapidly (time T 2 to T 3, fig 5) to the minimum plate voltage (E p min) of V 1. The circuit will then remain in this condition until another negative gate is applied (time T 3, fig 5).

c. Output variation.

(1) Referring to figure 5, it is apparent that the duration of the sweep is determined by the time of the negative gate T 1 to T 2. If the same circuit is to be used for longer sweeps, the interval from T 1 to T 2 must be increased. As indicated in figure 6, the dotted lines show that a wider gate pulse will allow C 2 to charge to a higher value of voltage.

(2) If a cathode ray tube (CRT) is to have several ranges available, the voltage amplitude for each sweep must be the same for a minimum amount of adjustment. If the duration (time) of the sweep is altered (fig 6), the amplitude of the sweep voltage changes accordingly; and if the duration is increased, the voltage amplitude will increase. To prevent this increase in voltage, the RC time constant must be made greater so that the capacitor will charge at a slower rate. This may be accomplished by changing the plate load resistor as shown in figure 7. If R 1 were left in the circuit for both the 5- and 20-mile ranges, the sweep would extend off the edge of the CRT on the 20-mile range and that portion of the sweep would be of no value. By switching a larger resistor (R 2) into the circuit, when the range is increased to 20 miles, C 2 charges at a slower rate and the amplitude of the sweep is approximately the same for both ranges.

4. TRAPEZOIDAL SWEEP GENERATOR.

a. General.

(1) The sawtooth sweep generators, as previously described, are suitable for any electrostatically deflected CRT. However, there are many electronic systems that employ electromagnetic deflection in the CRT circuits in which sweep voltages are applied to the coils. In long range sweeps the sawtooth voltage is adequate for a linear sweep, but for short ranges a special sweep voltage with a trapezoidal waveform must be applied to overcome the effects of the LR voltage drop of the sweep coils.

(2) In a magnetic CRT, the deflection of the spot depends upon a change in magnetic field strength. Since this strength varies directly with the current in the deflection coils, any linear deflection of the spot requires a linear variation of the current through the deflection coil.

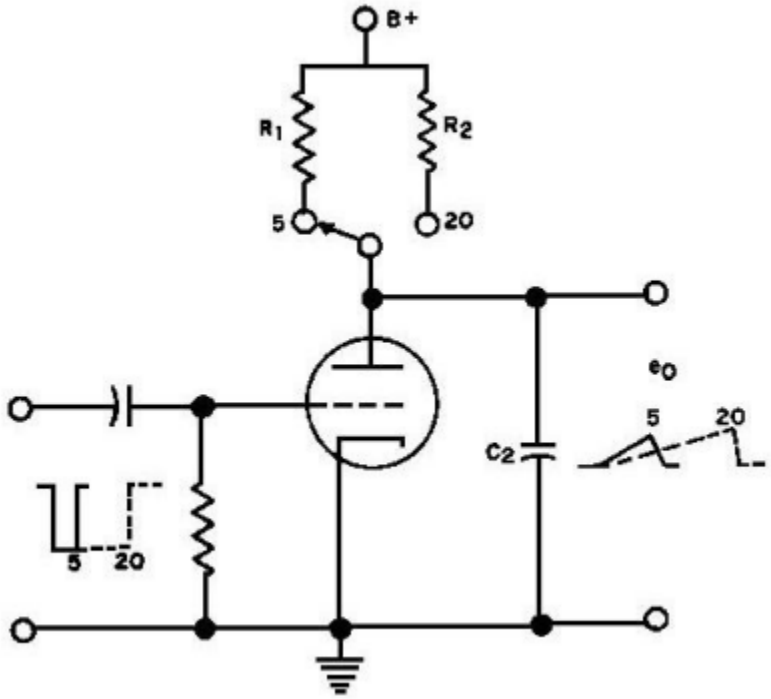


Figure 7. Increasing range of sweep.

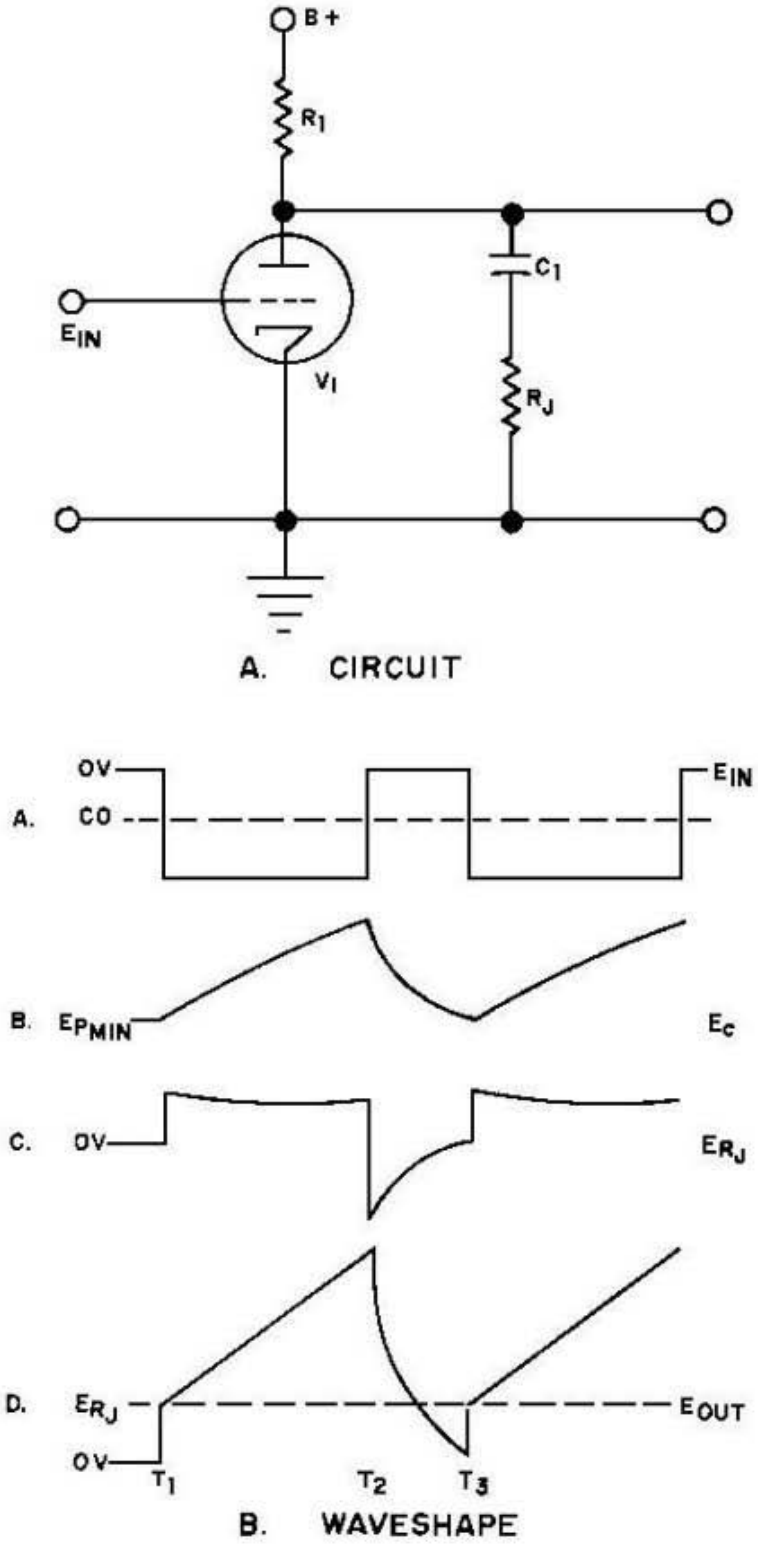


Figure 8. Trapezoidal sweep generator and waveshapes.

(3) The deflection coils of an electromagnetic CRT usually consist of many turns of fine wire. The inductance of such coils can be several hundred millihenrys and the resistance of the winding can be several hundred ohms. The exact values of inductance and resistance depend on the particular deflection yoke used. In addition, a small amount of distributed capacitance exists across the deflection coil. This capacitance usually can be neglected, except when high frequency or very short time duration sweeps are required.

(4) Because of the above-mentioned electrical constants, the shape of the voltage waveform that must be applied to the deflection coils to produce a linear sweep is not a sawtooth voltage. If a sawtooth voltage were applied to the deflection coils, a nonlinear sweep current would result. In order to produce a linear sweep and a sawtooth current, the voltage that is applied to the deflection coils is trapezoidal.

(5) The trapezoidal voltage applied to the deflection coils is made up of two components: one is a sawtooth voltage, which is required for the resistance of the deflection coil; and the other is a rectangular voltage, which is required for the inductance of the deflection coil. When these two voltages are added the resultant voltage is a trapezoidal waveform.

b. Circuit operation.

(1) Referring to figure 8, a vacuum tube and an RC circuit are used to produce the desired trapezoidal waveshape required by the sweep coils in a CRT. With no input trigger, the tube conducts very heavily and C 1 is charged to the plate-to-ground voltage of V 1. The circuit will remain in this condition until an external rectangular trigger is applied.

(2) When the negative-going input trigger is applied, V 1 cuts off and the plate voltage rises toward the applied voltage at the rate that the capacitor charges. At the first instant of voltage change, the capacitor acts as a short and the applied voltage is divided between the plate load resistor (R 1) and the jump resistor (R J). The voltage dropped across R J at this time is referred to as the jump voltage (C, fig 8) and its amplitude is directly proportional to its size as compared to R 1. After the first instant, the capacitor starts charging through R 1 and R J toward B+. Since only a small part of the charging cycle is used, a fairly linear rise is produced. This linear voltage rise is shown between time T 1 and T 2 in figure 8. The charging current is constant during the linear rise of the capacitor voltage and its magnitude is low because of the combined resistance of R 1 and R J. As a result, a constant low voltage is produced across R J, which is positive in respect to ground.

(3) At time T 2, figure 8, the input trigger rises to zero and causes V 1 to conduct. The low resistance of the triode is shunted across the circuit composed of C 1 and R J. The plate-to-ground voltage of V 1 drops toward the minimum plate value (E P min) of V 1 at the same rate that C 1 discharges. The voltage across C 1 falls rapidly from time T 2 to T 3, as the capacitor discharges through R J and V 1. During the discharge of C 1, a voltage drop appears across R J whose polarity is opposite to that produced during the charging time of the capacitor. The negative voltage has a greater magnitude than the positive voltage produced during charge time. This is true because the discharge current is considerably greater than the charge current (the resistance of R 1 is much larger than that of V 1). The time constant of the charge circuit is long because the charge current is limited by R 1 and R J. The discharge current is limited only by R J and the small resistance of V 1. Therefore, the time constant of the discharge circuit is short. C, figure 8, shows that the negative voltage across R J is reduced in amplitude from time T 2 to T 3. This occurs because of the exponential discharge current of C 1.

(4) When the sawtooth voltage across the capacitor (B, fig 8) is added to the approximately rectangular voltage across R J, a trapezoidal waveform is produced (D, fig 8). The linearity of the slope of this trapezoidal wave is determined by the ratio of the slope amplitude as compared to the applied voltage. If the sweep amplitude is 10 percent or less of the applied voltage, the sweep is considered to be linear. Therefore, the linearity of the sweep is determined by the time constant of R 1 and C 1 (R J is considered to be insignificant). If the size of C 1 is increased, the capacitor charges at a slower rate and the amplitude of the slope decreases. Therefore, the output linearity of the sweep would increase.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 5

1. What factor controls the conducting point of a thyratron tube?

   A. Frequency of the input trigger

   B. Value of the grid bias

   C. Duration of the input trigger

   D. Value of the de-ionization voltage

2. To what value can C 1 charge and still maintain a linear sweep in figure 1?

   A. 30 volts

   B. 70 volts

   C. 200 volts

   D. 300 volts

3. What is the result if R L is increased in figure 1?

   A. An increase in frequency

   B. A decrease in amplitude

   C. A decrease in frequency

   D. An increase in amplitude

4. How will an increase in the grid voltage (E c) affect circuit operation in figure 1?

   A. It will increase the output linearity

   B. It will decrease the time of each sweep

   C. It will increase the output frequency

   D. It will increase the amplitude of sweep

5. What voltage is used to externally synchronized a thyratron sweep generator circuit?

A. AC at a frequency always less than the natural frequency of the thyratron

B. AC at a frequency slightly greater than the natural frequency of the thyratron

C. DC of a value slightly greater than the ionization potential of the tube

D. DC of a value slightly less than the ionization potential of the tube

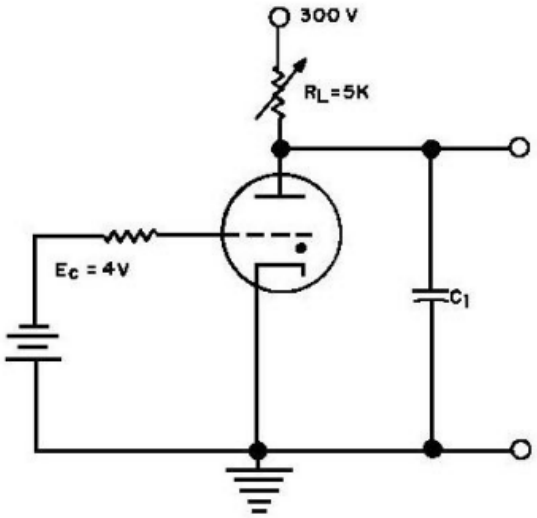


Figure 1.

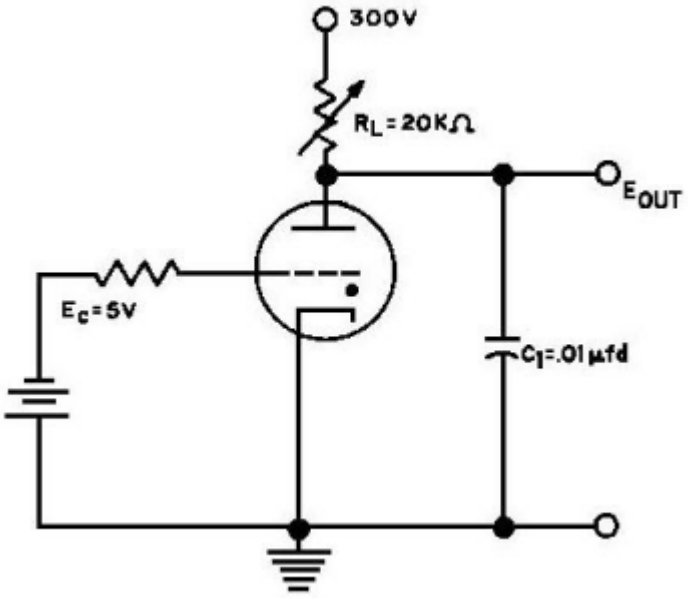


Figure 2.

6. In figure 2, what is the sweep amplitude, in volts, if the de-ionization potential is 14 volts and the plate-to-grid ratio is 10:1?

   A. 14

   B. 19

   C. 36

   D. 64

7. What characterizes a thyratron sweep generator?

   A. Long charge time constant and short discharge time constant

   B. Short charge time constant and long discharge time constant

   C. Long charge and discharge time constants

   D. Short charge and discharge time constants

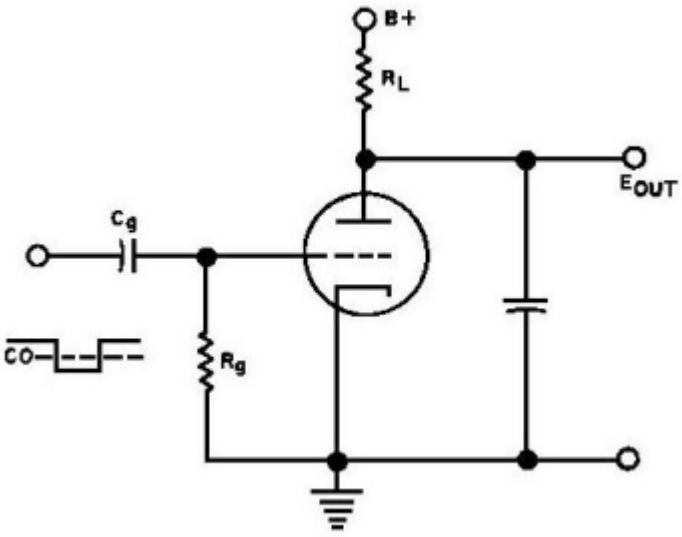


Figure 3.

8. What value determines the output frequency of the hard-tube sweep generator in figure 3?

   A. The product of R 1 and C g

   B. The product of R 1 and C 1

   C. The input gate amplitude

   D. The input gate frequency

9. What is the result if R L is decreased in figure 3?

   A. An increase in output frequency

   B. An increase in linearity

   C. An increase in output amplitude

   D. An increase in sweep duration

10. What is the output voltage condition if the filaments opened in the tube circuit in figure 3?

   A. B+

   B. Minimum positive

   C. Maximum negative

   D. B-

11. What is the result if the duration of the input gate is decreased in a hard-tube sweep generator?

   A. An increase in output frequency

   B. An increase in amplitude of the sweep

   C. A decrease in output frequency

   D. An increase in sweep linearity

12. What modification will cause an increase in the output amplitude of the sweep generator in figure 4?

A. Increase C 1

B. Decrease C 1

C. Increase R L

D. Decrease R g

13. Which sweep waveshape produces a linear sweep for CRT's with electromagnetic type deflection?

A. Trapezoidal

B. Sawtooth

C. Rectangular

D. Sinusoidal

14. What determines the amplitude of the jump voltage (E R J) in figure 4?

A. The size of R J as compared to C g

B. The size of R J as compared to R g

C. The size of R J as compared to R L

D. The size of R J as compared to C 1

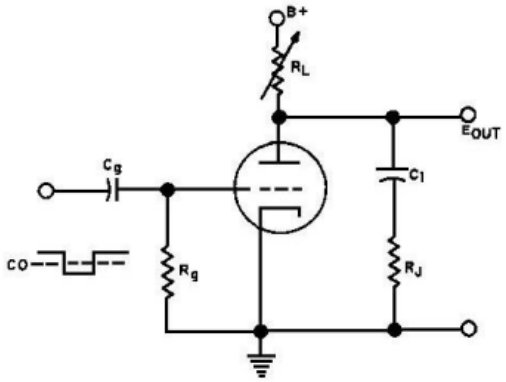


Figure 4.

15. Why is the discharge current greater than current in the sweep generator of figure 4?

A. The time constant of the charge circuit is larger

B. The resistance is larger

C. The time constant of the discharge circuit is larger

D. The resistance is smaller

16. How will an increase in R L affect the sweep generator operation in figure 4?

A. The output frequency will decrease

B. The jump voltage (E J) will increase

C. The output frequency will increase

D. The jump voltage (E J) will decrease

17. How will an increase in the input gate duration affect the sweep generator in figure 4?

A. The sweep linearity will decrease

B. The jump voltage (E J) will increase

C. The line voltage will decrease

D. The sweep linearity will increase

18. What BEST describes a hard-tube sweep generator?

A. It is free-running and synchronized by a positive input gate

B. It is externally triggered by a negative gate

C. It is free-running but synchronized by a negative input pulse

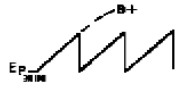
D. It is externally triggered by a positive pulse

19. What is the proper plate voltage waveshape of a hard-tube sweep generator?

A.

B.

C.

D. 

20. In figure 5, what component change, along with a decrease of input gate, will allow the range on an indicator to be changed from 50 miles to 5 miles?

A. An increase in R L

B. A decrease in C 1

C. A decrease in R g

D. An increase in C g

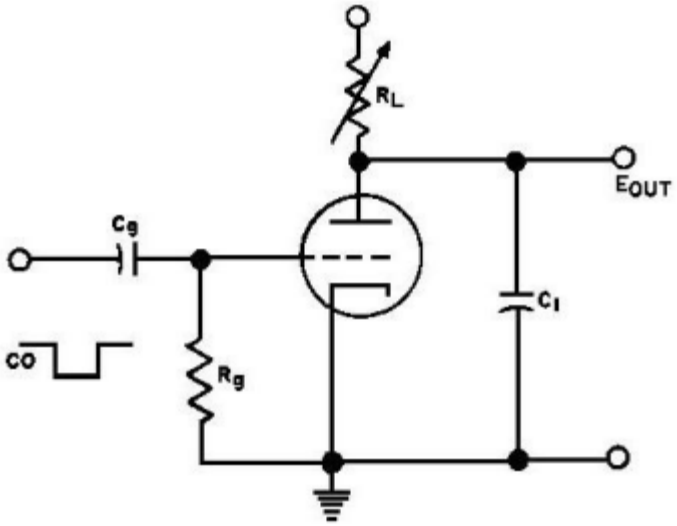


Figure 5.

LESSON 6. TRANSMISSION LINES AND WAVEGUIDES

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, description, characteristics, operation, and use of transmission lines.**
Lesson Credit Hours.....	**Four**

TEXT

1. INTRODUCTION.

a. In both radio and radar a connecting link must be provided between the transmitter and the antenna, or between the receiver and the antenna, and this link is called a transmission line. The transmission line transfers energy from the transmitter to the antenna, or energy from the antenna to the receiver. If the antenna could be built directly on the transmitter and receiver, there would be no need for the extended transmission line. However, even in a compact installation such as an aircraft, it is usually not convenient to locate the transmitter or receiver near the antenna.

b. Transmission lines are not used exclusively for conducting radiofrequency energy from one point to another. The lines that supply electrical energy to your house are transmission lines just as much as are the wires connecting one circuit to another. A transmission line can, therefore, be defined as a device for transmitting or guiding electrical energy from one point to another. A poor transmission line decreases the amount of energy available at the transmitting antenna for radiation or at the receiver for reception; a perfect transmission line delivers the entire output to the designated point.

c. RF transmission lines behave differently in different frequency ranges; for example, an RF transmission line designed to operate at the relatively low frequencies used in the standard broadcast range is not suitable for point-to-point aircraft communication systems. An RF transmission line can be expected to efficiently transfer energy from one point to another only at the frequency for which it is designed. This means that different kinds of transmission lines must be available for different frequency ranges.

2. TRANSMISSION LINES.

a. Types of transmission lines. The principal types of transmission lines are the twisted two-wire line, the spaced two-wire line, the shielded two-wire line, the flexible coaxial cable, and the rigid coaxial cable.

(1) Twisted two-wire line. The twisted two-wire line in figure 1 consists of a pair of insulated and twisted conductors. The twisting holds the lines together mechanically and aids in balancing each conductor to the influence of nearby magnetic and electrostatic fields. Twisted wires usually have a characteristic impedance of 70 to 100 ohms. Although the twisted line is flexible, occupies little space, and is simple to manufacture, it is not usable at radar frequencies because of capacitance between the wires, lack of shielding, and changes in characteristics due to moisture on the line.

Figure 1. Twisted two-wire line.

(2) Spaced two-wire line.

(a) The spaced two-wire line (fig 2) consists of two parallel conductors that are maintained a fixed distance apart by insulating spacers or spreaders. This line has two types–the spreader bar and the newer twin-lead line. The spreader bar type uses ceramic or polystyrene bars for spacing wires. The spacing may be up to six inches or more. The twin-lead line is the result of improved insulating materials and manufacturing techniques. It consists of two wires which are molded into a low-loss plastic called polyethylene. Impedances ranging from 75 to 300 ohms are available in the twin-lead line.

(b) Lines in general, however, may be constructed with any impedance up to 700 ohms by varying the wire diameter and spacing. The relationship between the characteristic impedance and the dimensions of a two-wire line is expressed mathematically by the equation, where D is the distance between wires (center to center), and d the diameter of one wire. The twin-lead line has a number of advantages over the spreader bar two-wire line. Wide spacing between the leads in the twin-lead type gives lower shunt capacitance between the leads. Insulation losses are lower in it, since the wires are separated by something other than air, unlike the wires in the spreader bar line. The spaced two-wire lines have two principal disadvantages. In the first place the line acts as an antenna. It will radiate energy. In the second place, nearby objects set up capacitance with the wires and disturb current flow through the line. This obstructs the orderly transfer of energy by the line.

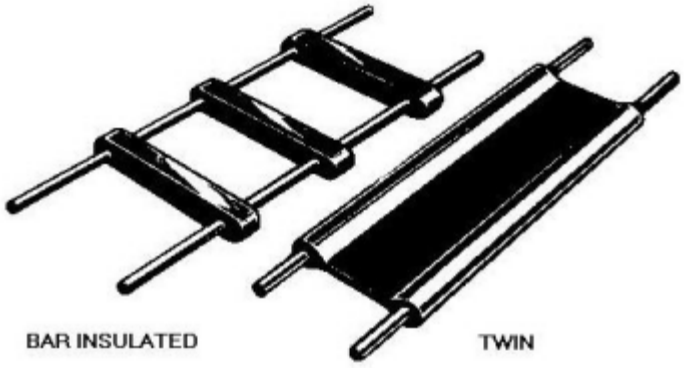


Figure 2. Spaced two-wire line.

$$Z_O = 276 \log \frac{2D}{d}$$

(3) Shielded two-wire line. A shielded two-wire line is similar to the two-wire spaced line except that it is shielded by a copper braid. Notice the practical form of this line in figure 3. The copper braid gives it flexibility. Flexibility could be obtained by using unbraided tubing. However, the use of braid permits uniform spacing of each conductor during manufacture. This results in each wire being perfectly balanced capacitively to the surrounding conductor. As long as the balance is maintained, certain detrimental effects, such as high capacity to ground when the shield is grounded, are very slight. This line does not radiate energy because of the shield and thereby is not affected by nearby magnetic fields.

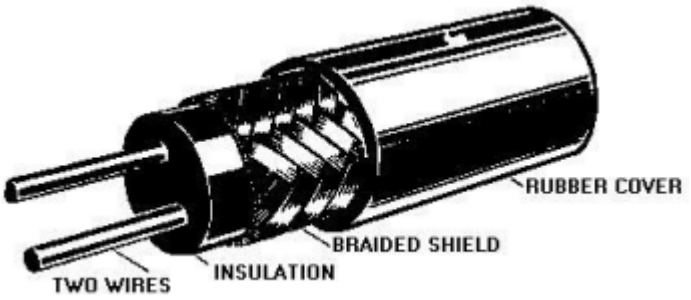


Figure 3. Shielded two-wire line.

(4) Coaxial line.

(a) The coaxial line is the most universally used type of line for r-f transmission. It consists of two conductors. One of the conductors is hollow; the other conductor is located inside the hollow conductor. The two conductors are made concentric in cross section to maintain uniform characteristics. Early coaxial lines were made of copper tubing in which there was a wire held in the center by ceramic or polystyrene washers or beads. Attempts to build flexible cables led to the use of outer conductors of copper braid spaced by a continuous row of beads or rubber insulators. But rubber insulation caused excessive losses at high frequencies. In addition the bead arrangement permitted air to enter the line, causing moisture to collect. This resulted in high leakage currents and arc-over when high voltages were applied.

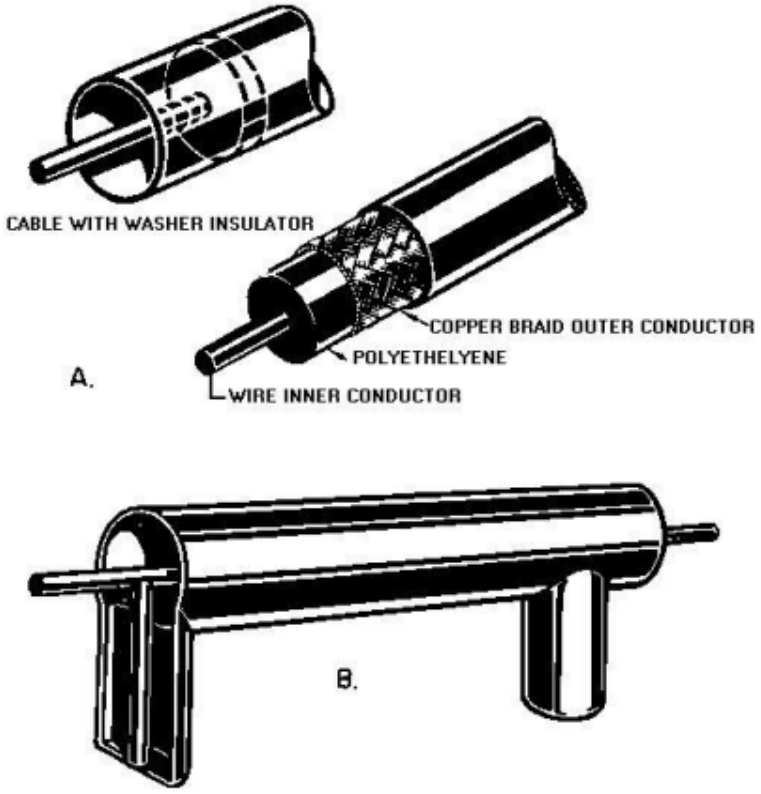


Figure 4. Coaxial cables.

(b) Research solved this problem by using polyethylene plastic, a hard, solid material, safely flexible over a temperature range of -40 degrees to +80 degrees C. Polyethylene is unaffected by such fluids as acids, alkalis, aviation gasoline, oil, hydraulic brake fluid, and seawater. Furthermore, there is no known solvent for polyethylene at ordinary temperatures. Its extremely low losses at high frequencies is important for radar. At 200 MHz the losses may be only one-hundredth of those of rubber under certain conditions. When carefully manufactured, a coaxial cable insulated with polyethylene (fig 4A) will be uniform within .005 inch and will have no air between the conductors. Thus, due to its uniform characteristics, it will operate indefinitely with low leakage and with little danger of arc-over.

(c) Where installations require still lower losses, such as 3000-MHz airborne radar installations, an air-insulated rigid coaxial cable meets these requirements. In this cable (fig 4B) the center conductor is supported with metallic insulators which are quarter-wave sections of coaxial line. Since there is air in the interior, the interior of the line is usually pressurized to keep moisture out.

(d) Coaxial lines have a number of advantages. The shielding is perfect for both magnetic and electrostatic fields. Because of this a coaxial line does not radiate, it also does not pick up any energy. Therefore it can be installed anywhere without being influenced by other strong fields. Also, its capacitance is lower than that of a shielded pair line.

b. Impedance in transmission lines.

(1) In addition to the normal resistance and inductance values of any conductor, a transmission line has a certain value of capacitance between the conductors. This is illustrated by the short sections of line in figure 5. The equivalent circuit for these short line sections may be represented by the lumped values of inductance, capacitance, and resistance. Just as many short sections of line can be connected in series to form a long transmission line, so an equivalent circuit is most accurately represented by placing a number of small lumped sections in series: B, figure 6, shows why this would more closely represent the distribution of constants along an actual line than would one large equivalent circuit of inductance, capacitance, and resistance (A, fig 6). Thus, a circuit composed of many small sections will more closely approximate an actual line in operation.

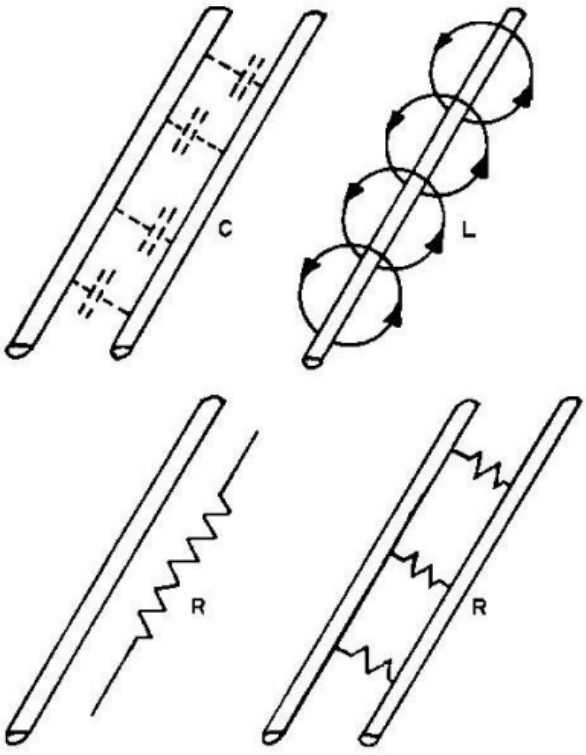


Figure 5. Resistance and reactance along a line.

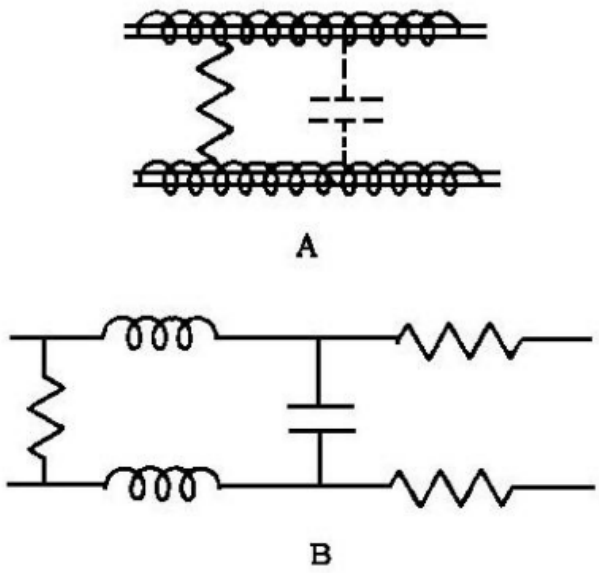


Figure 6. Equivalent circuit of a line section.

(2) If a signal is applied to one end of a transmission line, a definite value of current flow can be measured through the line. The ratio between the applied voltage and the current through the line is determined by the impedance of the line and is usually designated as Z_o. Z_o represents not only the pure resistance of the conductors in the line, but also the distribution of the inductive and capacitive reactances in each small section. It is known as the characteristic impedance of the line. In most radiofrequency lines the resistance is very small as compared to the reactance, and the characteristic impedance may be calculated by the simplified formula $Z_o = \sqrt{L/C}$, using the actual values of L and C as found in the line.

(3) In order to have a maximum amount of power delivered to a load, the impedance of the load must be equal to the impedance of the generating source. If the transmission line is the path over which energy flows between the source and the load, then it, too, must match the impedance of both the generator and the load in order to transfer maximum power. This is easier understood if the transmission line is imagined to be a new load placed across the generating source. In this case, if the impedance of the line is equal to the impedance of the generator, maximum power will be transferred to the line. Again, if the line has minimum losses within itself, maximum power will be available for transfer to the load placed across the output end. In this manner, the line may be thought of as a new generating source whose output has the same value and shape as that of the original generator. Hence, in order for the line to transfer maximum power to the load, the impedance of the load must be equal to the characteristic impedance of the line. From this, it is apparent that if a transmission line is properly used a thorough understanding of its impedance characteristics is necessary. This is especially true at higher frequencies because any slight physical error in the line may alter its impedance enough to cause a mismatch in the system. Should this occur, then serious losses in power and extreme distortion will result.

c. Losses in transmission lines.

(1) Theoretically, a perfect transmission line would have no losses, although the actual line will always show some decrease between its input and output energy levels. These losses may be divided into two classes: those which are inherent in the physical design of the line, and those which are the result of poor matching between the characteristic impedance of the line and its input and output impedances.

(2) The first class of losses is determined by the pure resistance in the conductors and by the leakage resistances in the dielectric of the line. Therefore, once a particular type and size of transmission line has been selected for a job, little can be done to control these losses. However, the second class of losses is a direct result of the manner in which the line matches the input and output circuit impedances. In most cases, this will constitute the greater portion of power drop across the line.

(3) These losses are controllable by selecting and adjusting the line for proper transfer of power at a particular operating frequency. Primarily, the energy losses appear as heat dissipation and as radiation from the line. They may range from a negligible value, in a properly matched system, to such large amounts that nearly all of the power is expended within the line when it is poorly matched to the rest of the system.

d. Line theory.

(1) Incident wave. If a source of voltage is applied to a transmission line the voltage will appear at a point some distance down the line after a time delay. This is true regardless of whether the voltage change is a jump from zero to some value, a drop from some value to zero, or for that matter, any other change in voltage such as a RF signal. Whatever the change, the voltage will be conducted down the line at a constant rate. This time delay is caused by the series inductance and the shunt capacitance of the line (see figure 7). When the switch is closed, the capacitors will charge one after another. This arrangement of coils and capacitors is often used in electronic equipment as an artificial transmission line to produce a time delay. If you know the amount of inductance and capacitance of the line, you can easily compute the time required by any waveform to travel the length of the line. Time is equal to the square root of the product of the inductance and capacitance of a given length of line. $T = \sqrt{LC}$

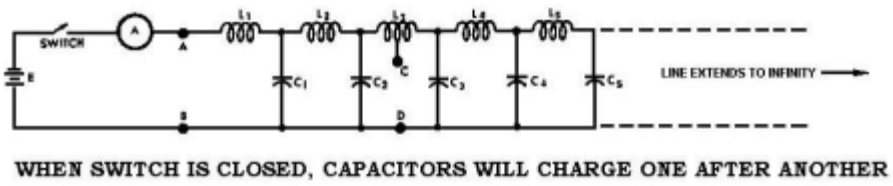


Figure 7. Transmission line time delay.

(2) Reflected wave. After the voltage (and current) applied to a transmission line reaches the end, the power will be dissipated by the load. (If the load impedance is equal to the characteristic impedance of the line) or the amount not dissipated (due to a mismatch between the load and the line), will be reflected back down the line to the source, thus, upsetting the match in impedance between the source and the line. This change in impedance will change the amount of power the source must furnish the line to sustain both the incident and reflected waves of energy along the line.

(3) Standing waves.

(a) Production of standing waves. If a RF signal is applied to a transmission line which is not terminated by a load impedance equal to the characteristic impedance of the line, the RF signal or part of it will be reflected as stated in paragraph (2) above. Since the incident and the reflected waves are of the same frequency and both travel along the line at the same speed, but in opposite directions, there will be points along the line where the two waves will always be 180 degrees out of phase, and at other points where they will always be in phase.

(b) Detection of standing waves: If an RF detector is moved along a transmission line which is not matched to the load, as shown in figure 8, the points where the incident and reflected waves are always in phase would produce a maximum signal. These points are referred to as loops and the points where the two waves are always 180 degrees out of phase would be detected by a minimum signal. These points on the line are called nodes.

(c) Standing wave ratio. The ratio of maximum RF current (loops) to minimum RF current (nodes) along a line is called the standing wave ratio (abbreviated SWR). The standing wave ratio is a practical measurement which gives a good indication of the impedance match between the line and the load. The higher the SWR the greater the mismatch between the line and the load. With no mismatch between the line and the load there would be no reflected wave of current or voltage and the amplitude of the detected RF current along the line would always be the same without loops or nodes, thus, the SWR would be 1 to 1.

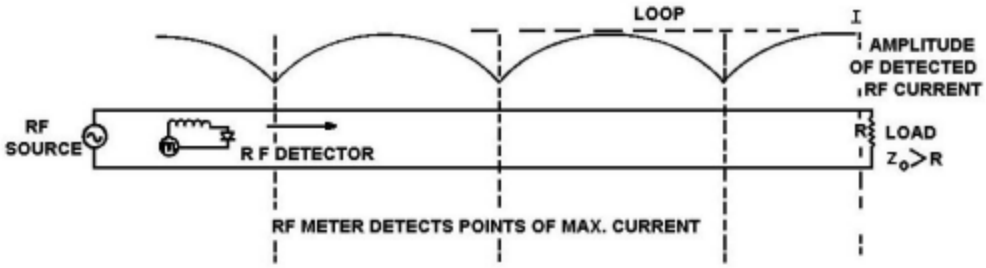


Figure 8. Detection of standing waves.

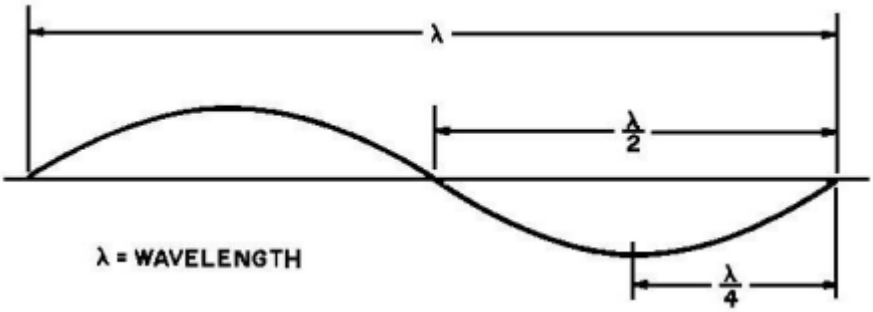


Figure 9. Wavelength along a line.

(d) Position of standing waves on a line.

1. The position of loops and nodes along an improperly matched transmission line can easily be calculated mathematically if certain things are known, such as, the frequency of the applied RF, the characteristic impedance of the line, the impedance or reactance of the load, and the velocity at which the energy travels down the line. The distance between a loop and a node will always be one quarter of a wavelength. See figure 9. A wavelength is designated by the Greek letter λ. The general formula for calculation of a wavelength is:

$$\text{Wavelength (meters)} = \frac{\text{Velocity of propagation (m/sec)}}{\text{Frequency (hertz)}}$$

2. The velocity at which RF energy is propagated through free space is 300,000,000 meters per second or 186,000 miles per second. This is the same as the velocity of light in free space. The velocity of propagation of RF waves along a transmission line may be considerably different. For example, in figure 10, the values of K express the ratio of the actual velocity of the energy on the line to the velocity of light. Therefore, a more practical formula for calculating the wavelength of energy on a line would be:

$$\lambda \text{ (meters)} = \frac{K \times 3 \times 10^6 \text{ (meters per second)}}{\text{Frequency (hertz)}}$$

where K is the velocity factor of a specific type of transmission line.

TYPE OF LINE	K
Two-wire open line (wire with air dielectric)	0.975
Parallel tubing (air dielectric)	0.95
Coaxial line (air dielectric)	0.85
Coaxial line (solid plastic dielectric)	0.66
Two-wire line (wire with plastic dielectric)	0.68 - 0.82
Twisted-pair line (rubber dielectric)	0.56 - 0.65

Figure 10. Velocity factors.

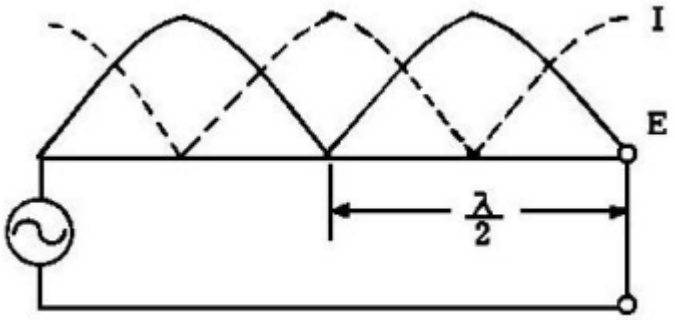


Figure 11. Standing waves on a shorted line.

3. Position of standing waves on a shorted line.

a. As indicated by its name, the shorted line is a transmission line whose load end is directly shorted. Therefore, it is apparent that no voltage can exist across this perfect short circuit. To obtain a zero voltage at the shorted end, a wave whose magnitude is equal to the magnitude of the incident wave, but opposite in phase, must be reflected from the shorted end. Hence, the incident and reflected waves cancel out at the shorted end and the net voltage (standing wave voltage) is zero at this point.

b. Since the incident and reflected waves travel in opposite directions, the two voltages do not cancel out at every point on the line. For example, at a point a quarter-wavelength from the shorted end the two voltages are in phase with each other. In this case, the amplitude of the resultant standing wave is twice the amplitude of either the incident or reflected wave alone. This distribution of standing waves of both voltage and current is shown in figure 11. At the point of the short circuit the voltage is zero and the current is maximum. The voltage rises sinusoidally to maximum a quarter-wavelength from the short, drops to zero at a half-wavelength point ($\lambda/2$), and then repeats for each half-wavelength of the line. As previously mentioned in this paragraph, the amplitude of the standing wave voltage is twice that of the original wave. This standing wave pattern indicates that all energy traveling down the line is reflected by the load; i.e., the load absorbs no energy.

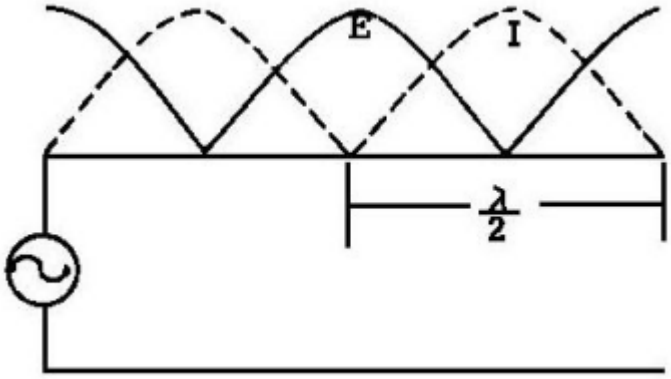


Figure 12. Standing waves on an open line.

c. The current at the short-circuited point is at a maximum value because the resistance of the short circuit is zero. Hence, the development of the standing wave of current is different from that of the voltage. In the case of the circuit, the reflected wave is in phase and of equal magnitude with the incident wave at the point of the short circuit. Therefore, the standing wave of current is at its maximum amplitude at the short circuit. A quarter-wavelength away from the short circuit, the current waves are 180 degrees out of phase and the value of the standing wave is zero. Thus, the standing wave of current has the same form as the voltage standing wave, but it is displaced a quarter-wavelength (90 degrees out of phase).

d. At the short circuit, where the voltage is zero and the current is maximum, the impedance is zero. The amount of impedance changes as the ratio of voltage to current varies along the line. As the voltage amplitude rises and the current decreases, the impedance increases. At a point one quarter-wavelength from the short circuit, where the voltage is maximum and the current is zero, the impedance is infinite. In the next quarter-wavelength, the impedance of the line drops from infinity to zero as the voltage-current ratio is reversed. Thus, the impedance varies from point to point all along the line.

4. Position of standing waves on an open line.

a. An open-end line is a transmission line of finite length having no load connected to its output. Thus, the output impedance is infinitely high and the current will be zero with no energy expended in the load. As the result of the open termination, there is maximum reflection along the line and minimum loss of energy due to line resistance. This high degree of reflection makes an open line very valuable as an impedance device, such as a matching stub or transformer.

b. As shown in figure 12, the maximum voltage point and the minimum current point are always fixed at the line termination, regardless of the frequency applied. The voltage standing wave falls to zero a quarter-wavelength away and rises to a maximum at the half-wavelength point. The current standing wave rises to a maximum at the quarter-wavelength point and falls again to zero at the half-wavelength point. The impedance at various points along an open line changes regularly with the current and voltage amplitudes. For instance, if a point on the line is taken where the voltage waveform is at a minimum and the current is maximum, then, according to formula Z = E/I, impedance will be very small. As the relationship between voltage and current changes through each wavelength, the relative impedance (Z) changes accordingly.

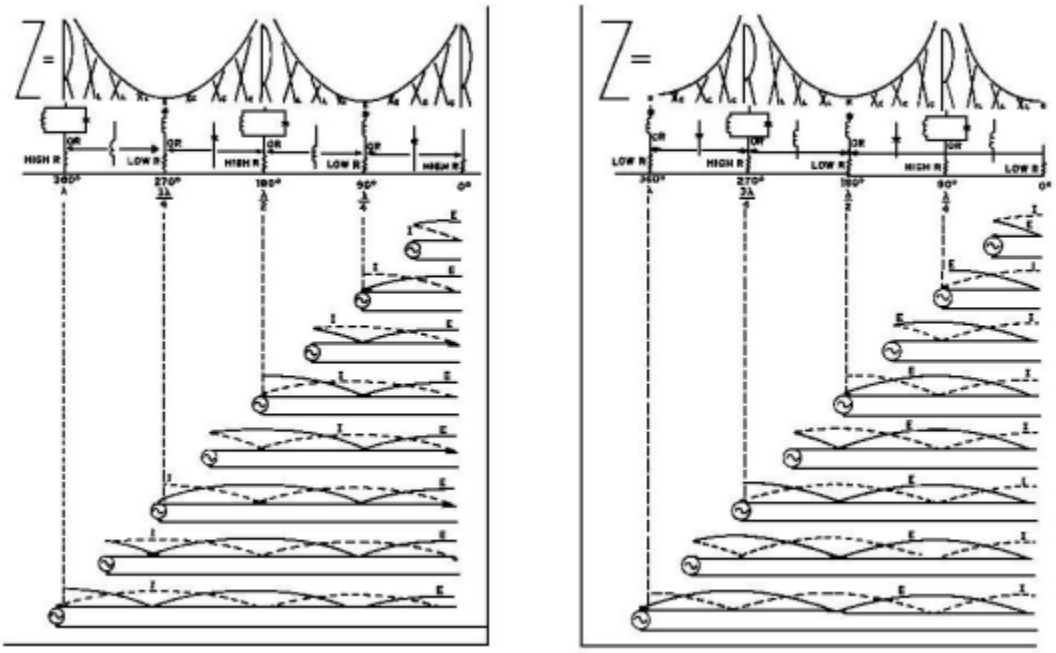


Figure 13. Impedance charts.

(e) Impedance chart for open and shorted lines. Figure 13 shows the relation of voltage, current, and impedance for various lengths of both open-end and closed-end transmission lines. Directly above the line is shown the impedance which the generator sees for various lengths of line. The curves above the letters of various height indicate the relative values of the impedance presented to the generator as it moves from right to left. The circuit symbols indicate what the equivalent electrical circuits are for the transmission lines at that particular length. The standing waves of voltage E and current I, whose ratio is the impedance Z, are shown without polarity above each line.

e. Application of transmission lines.

(1) Transfer of energy. One of the most important applications of transmission lines is the transfer of power over various distances. Lines used for this purpose are usually of two-wire or coaxial type. These lines are employed extensively for commercial power transfer, telephone lines, and as connecting links between radio transmitters and antennas.

(2) Impedance matching devices.

(a) Transmission lines, in addition to transmitting power from point to point, are also used as metallic insulators, wave filters and chokes, and impedance matching devices. In the RF spectrum, resonant line sections are used principally for impedance matching. Usually, they are in some form of matching stub or transformer and are applied to a transmission system in order to match a generator and a load that have different impedances.

(b) When a quarter-wave line is short circuited at the output end and is excited to resonance at the other end by the correct frequency, there are standing waves of current and voltage on the line. At the short circuit (fig 14A) voltage is zero while the current is maximum. At the input end the current is almost zero and the voltage is maximum. Therefore, from the formula Z = E/I, the input impedance is seen to be very great. An exceedingly high impedance across the terminals appears as an insulator to another line connected to the input end; hence, such a line can be used as an insulator at its two open terminals, although limited to one particular frequency.

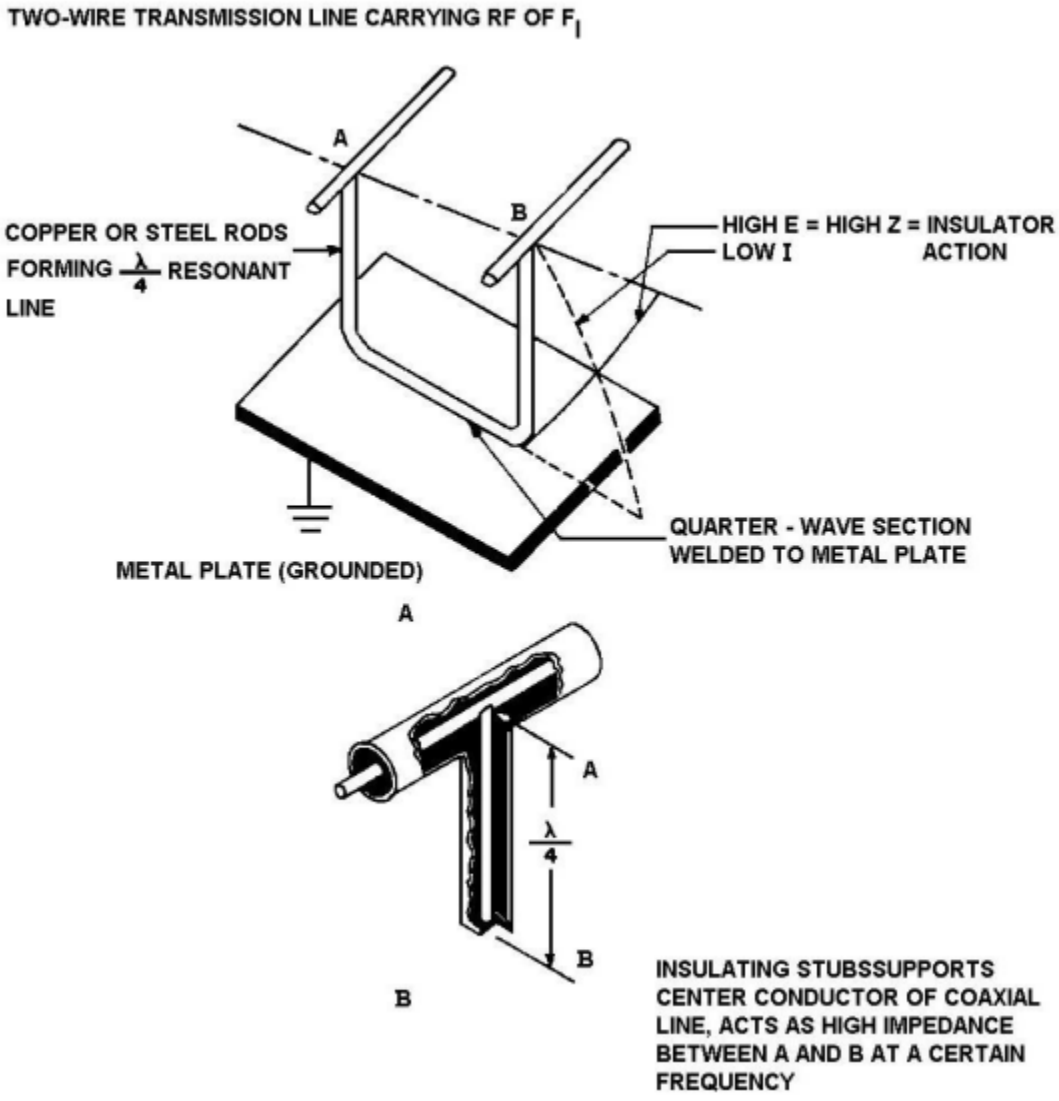

TWO-WIRE TRANSMISSION LINE CARRYING RF OF F_I
A
B
COPPER OR STEEL RODS FORMING $\frac{\lambda}{4}$ RESONANT LINE
HIGH E = HIGH Z = INSULATOR ACTION
LOW I
QUARTER - WAVE SECTION WELDED TO METAL PLATE
METAL PLATE (GROUNDED)
A
A
$\frac{\lambda}{4}$
B
B
INSULATING STUBSSUPPORTS CENTER CONDUCTOR OF COAXIAL LINE, ACTS AS HIGH IMPEDANCE BETWEEN A AND B AT A CERTAIN FREQUENCY

Figure 14. Quarter-wave transformer.

(c) Another important application of the quarter-wave insulator is the teeing of coaxial lines. It has been noted that the inner conductor of a coaxial line must be separated and insulated from the outer conductor. This is generally done by filling the space between the two conductors with a dielectric material, or by using dielectric beads or spacers. The dielectric insulator has the disadvantage of introducing dielectric losses in the line, especially at the higher frequencies. As shown in B, figure 14, a quarter-wave stub used to separate and insulate the inner and outer conductors reduces the dielectric loss. Consequently, if the quarter-wave stubs or tees are spaced close enough to provide adequate mechanical support they are more efficient than spacers, provided the line operates at only one frequency or over a narrow band of frequencies.

(d) To match a line to an antenna, the point along the line where the resistive component is equal to the characteristic impedance (Z o) is first determined. The reactance at this point can then be canceled out with a section of line or stub (fig 15). If the line reactance at this point is inductive a capacitive stub is used, if the line is capacitive an inductive stub is used. The stubs, constructed from parallel conductors or coaxial lines, are inserted in the line at a point determined by measurements and calculations. The problem of finding the exact point on the line where the resistive component is equal to Z o and what length stub to use is solved with a standing wave meter and appropriate tables. The stubs are adjusted during installation by measuring the standing wave ratio along the line and positioning the stub for a minimum ratio.

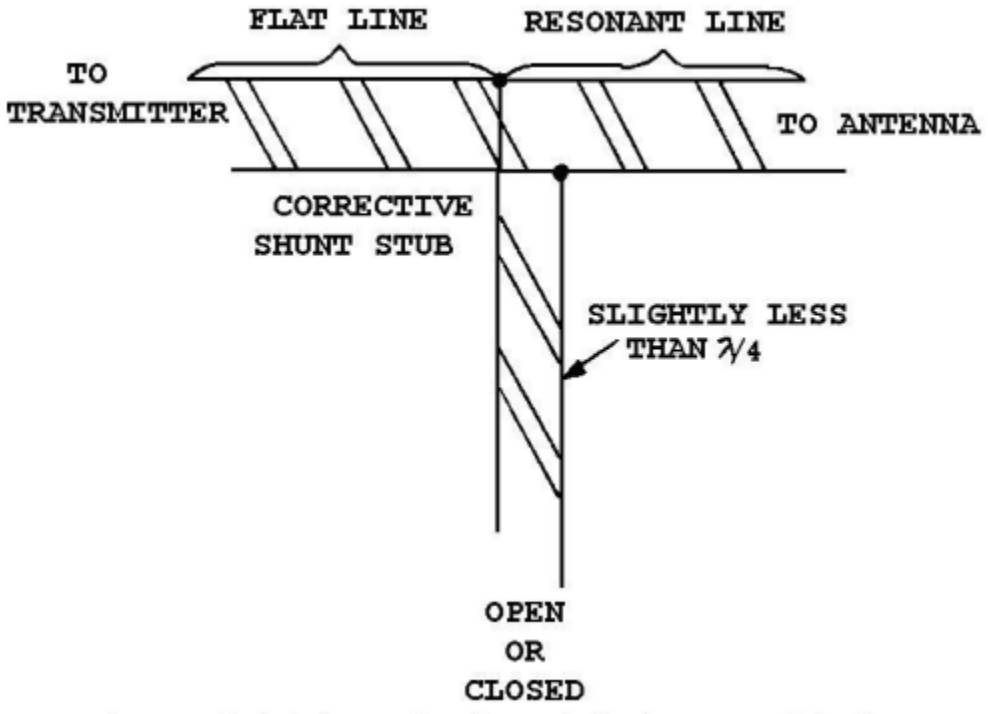


Figure 15. Method of connecting a "corrective" stub to a transmission line.

(e) Another method of matching the transmission line to the antenna makes use of matching line sections. These sections are, in effect, transformers which correctly match two lines having different characteristic impedances. As mentioned in (a) above, a common example is the matching of a particular transmission line to an antenna whose impedance is different from that of the transmitter and line. In this case, a point is located where the reactance is zero and the line has only a resistive component. Generally, half- or quarter-wavelength sections will minimize losses within the section. The formula for calculating the correct impedance needed by the matching line section for maximum power transfer is $Z_o = \sqrt{ZS \times ZR}$ (fig 16).

(f) Although the delay characteristics and charging action of RF transmission lines make them useful in some radar applications, they are too long and bulky for lower frequency applications. For this reason, artificial transmission lines, which possess all the characteristics of actual lines except bulk and length, are used as time delay lines and as pulse forming networks for modulator pulses. The artificial lines are built by first determining the capacitance and inductance needed for the desired line, and then constructing the line with equivalent lumped inductors and capacitors.

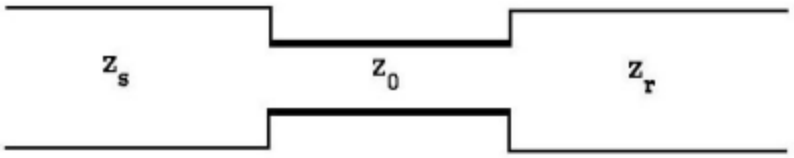


Figure 16. Impedance matching line section between two lines.

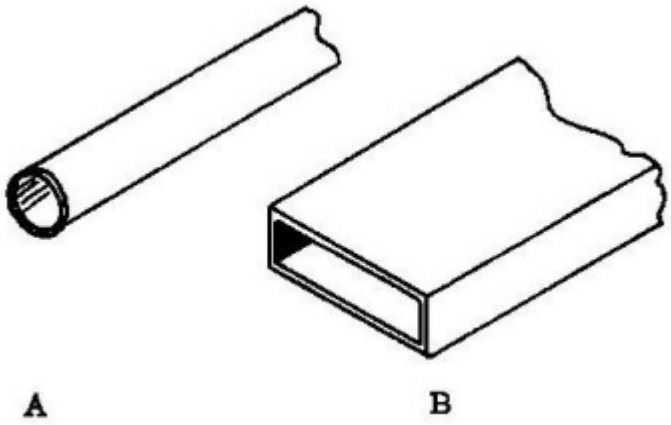


Figure 17. Cylindrical and rectangular waveguides.

3. WAVEGUIDES.

a. Introduction.

(1) Some electronic equipment used by the military services operates at frequencies above 1,000 MHz. Because of the very short wavelengths of these frequencies they are called microwaves. Transmission lines employed at these frequencies are physically and electrically different from those discussed in the preceding paragraphs.

(2) The reason for using special transmission lines at microwave frequencies is that the conductors increase the amount of energy radiation as the frequency increases. This radiation effect increases to a point where, if a microwave signal were applied to a two-wire line, most of the energy would be radiated into space and practically none would reach the output end.

(3) Even though the inner conductor of a coaxial line does not radiate energy, and the coaxial line is more efficient than the open wire line, supporting the center conductor of the line presents a problem at microwave frequencies. If a solid dielectric is used as a support, the losses at microwave frequencies are relatively high. If any other support is used, the coaxial line is frequency sensitive; i.e., only a limited range of frequencies can be transmitted without serious losses. A hollow conductor known as a waveguide is a more efficient transmission line for microwave frequencies.

(4) A waveguide is a properly dimensioned, hollow metal pipe (usually rectangular) having the property of conducting high frequency electromagnetic energy with very little loss. (See figure 17.) The energy moving down any transmission line is contained in an electromagnetic wave which is guided by the conductor.

b. Advantages of waveguides.

(1) General. Waveguides have certain advantages and disadvantages when used to transmit microwaves. The first advantage - there is no radiation loss - indicates why waveguides are preferred to coaxial lines. The disadvantages pointed out in paragraph c show why waveguides are used only for microwaves.

(2) A waveguide has no radiation loss. At microwave frequencies, ordinary conductors radiate most of their applied energy. Consequently, in the case of two-wire or single-wire lines large radiation losses occur. In waveguides, however, radiation losses are practically zero because all of the electromagnetic energy is confined inside the guide.

(3) A waveguide has no dielectric loss. One of the major reasons for signal attenuation in a coaxial line is the leakage in the dielectric supporting the inner conductor. Due to the dielectric material's resistance some transmitted energy is absorbed by the insulator. The amount of electromagnetic energy absorbed by the dielectric is directly proportional to the frequency of the transmitted energy. The dielectric loss, which is much higher at microwave frequencies than at the lower frequencies, is eliminated by the waveguide since there is no requirement for a solid dielectric support.

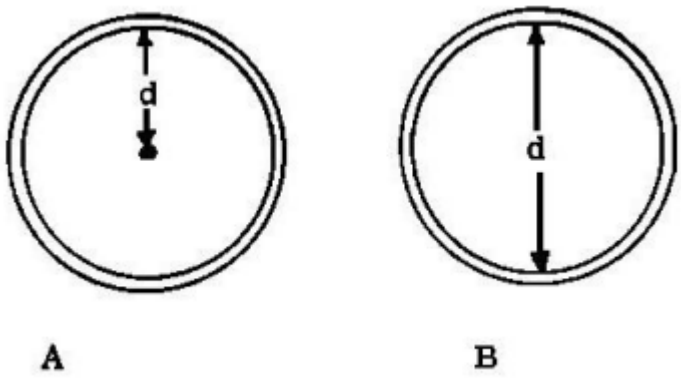


Figure 18. Breakdown paths of coaxial line and waveguide.

(4) A waveguide has low skin-effect loss. When an electromagnetic wave strikes a conductor, a current is induced in that conductor and, because every conductor has some resistance, energy is dissipated in the form of heat. The amount of energy lost is directly proportional to the effective resistance of the conductor. If the resistance is high, the losses are also high. The effective resistance of a conductor is determined by its DC resistance, the cross-sectional area, and the frequency of the energy being transmitted. In a coaxial cable the DC resistance of the inner conductor is very small. The cross-sectional area of the inner conductor, however, is smaller than the cross-sectional area of the outer conductor. Since the resistance of a conductor is inversely proportional to the cross-sectional area, the effective resistance of the inner conductor is much higher than that of the outer conductor. As the frequency of the transmitted energy is increased, the effective resistance of the conductor also increases. This is due to the skin effect, which means that energy at the higher frequencies tends to travel along a conductor's surface. Since this effect reduces the cross-sectional area, it also increases the effective resistance. The removal of the center conductor in a coaxial line eliminates it as a cause of skin-effect loss, and in effect, converts the coaxial line into a waveguide. The larger inner surface of the waveguide considerably reduces the skin-effect loss.

(5) The waveguide has a high efficiency of transmission. As a result of the three advantages previously discussed, the waveguide provides a very efficient transmission line for microwave energy. It eliminates the radiation loss of the two-wire line and the dielectric and inner-conductor losses of the coaxial cable; therefore, signals whose frequencies exceed 2,000 MHz are usually transmitted through waveguides.

(6) The waveguide has a high power-handling ability. In any transmission system, the ability to transmit high power is usually limited by the system's ability to handle high voltages. In a coaxial transmission line, the ability to handle high voltage is limited by the distance between the inner and outer conductors and the type of dielectric used. The larger the diameter of the line, the greater the power-handling capacity. If the diameter of the cable were too small for a given transmitted power, the voltage would arc over from the center conductor to the outer or ground conductor. A waveguide of the same diameter, however, will handle a higher voltage than the coaxial line. This can be seen in figure 18 where A shows a coaxial line with a distance d for a waveguide of the same outside diameter is over twice that of the coaxial line. Therefore, the waveguide can handle a much higher voltage and, consequently, a much higher power than the coaxial line.

c. Disadvantages of waveguides.

(1) The coaxial line has a frequency above which its losses become too great for practical use. The waveguide, on the other hand, has a frequency below which its losses become too great for practical use. The frequency at which this occurs is known as the cutoff frequency. At frequencies below the cutoff frequency, the attenuation in waveguides is much greater than for an equivalent coaxial line.

(2) In general, the cutoff frequency varies inversely with the dimensions of the waveguide. This relationship is such that waveguides become practical only at microwave frequencies. For example, in order to transmit energy at a frequency of 300 MHz, a 2- or 3-foot waveguide is necessary. The physical size of such a waveguide makes its use impractical. At a frequency of 3,000 MHz, however, the waveguide need only be about 2 or 3 inches wide. This practical dimension may be handled with relative ease. Thus, since a waveguide passes only frequencies above the cutoff frequency, its use is limited to the microwave frequency range.

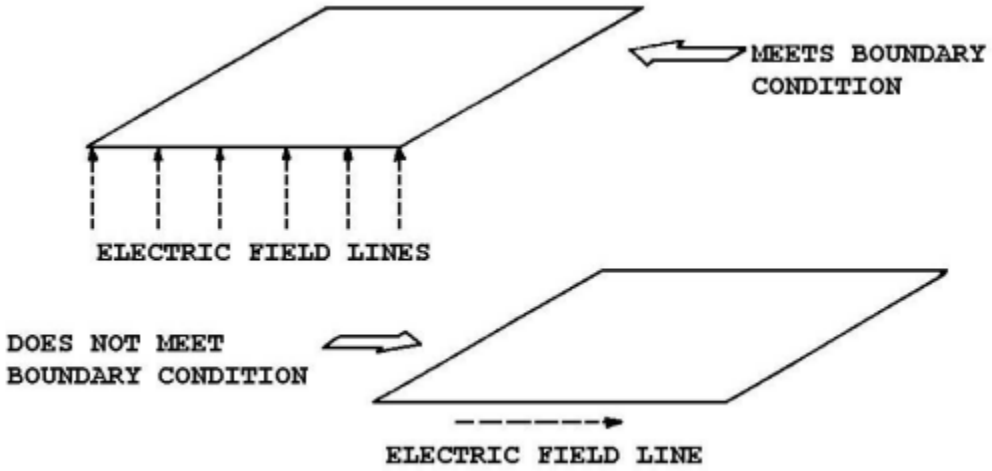


Figure 19. Boundary condition for an electric field.

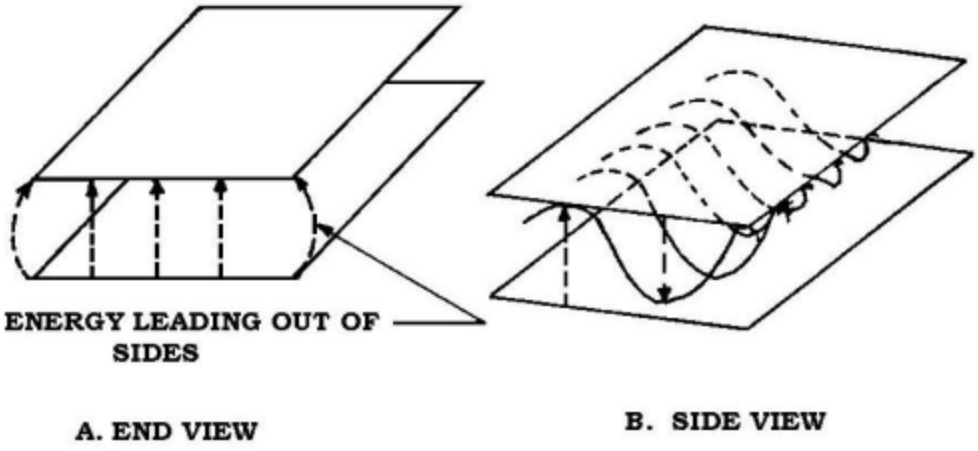


Figure 20. Electric field between plates.

(3) Another disadvantage of the waveguide involves installation problems that are not associated with two-wire or coaxial lines. Waveguide installations are often referred to as electrical plumbing because the exact positioning and rigidity required calls for techniques well known to plumbers and less known to electronic or microwave technicians.

(4) Special couplings are required to fasten waveguide lengths together. At the lower radiofrequencies ordinary soldering of the conductors assures adequate transmission characteristics. At microwave frequencies, however, special precautions must be taken to prevent the leakage of any energy. Ideally, the waveguide should be one long, continuous section between the transmitting and receiving points. However, the waveguide is usually made in fairly short sections which must be properly connected.

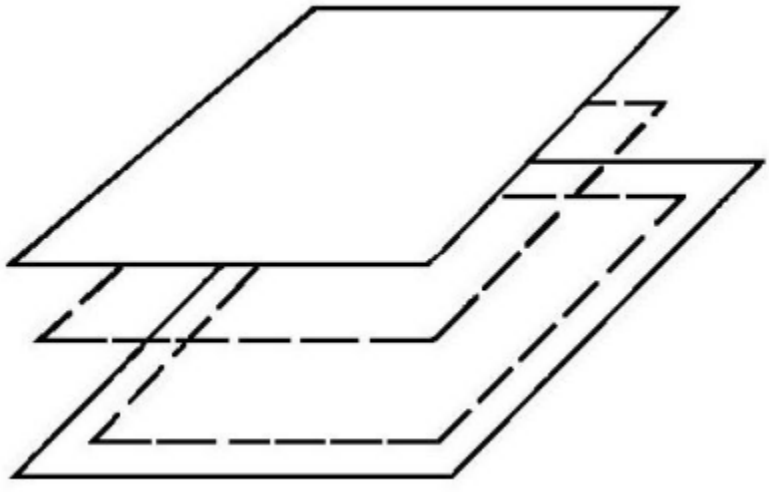


Figure 21. Magnetic loops between plates.

(5) The specialized nature of a waveguide's installation increases its cost over that of a coaxial installation. The price of the guide is high because of the rigid mechanical specifications it must meet in order to prevent discontinuities (permitting energy losses) along the transmission path. Also, in some applications, the inside of the waveguide may be silver-plated or even gold-plated to reduce the skin-effect losses. Again, this increases the cost.

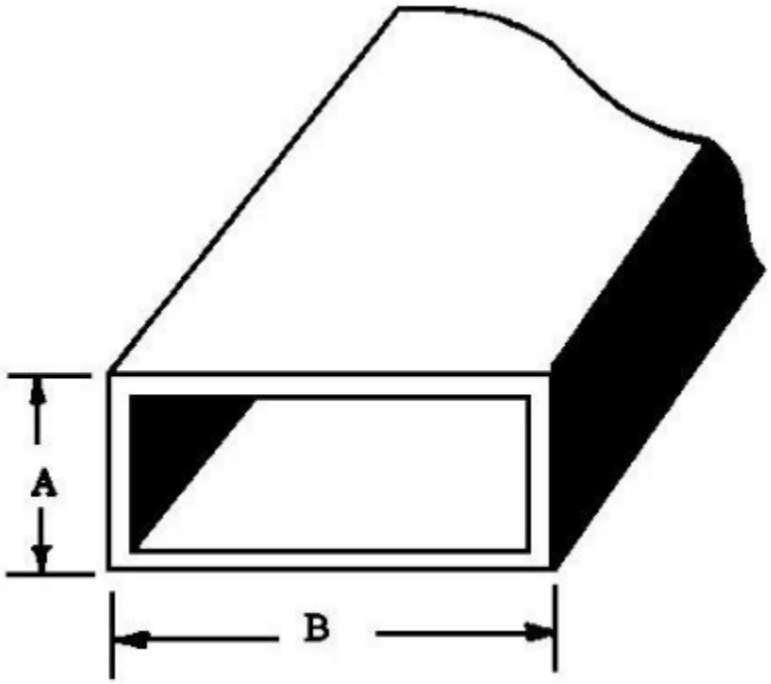


Figure 22. Rectangular waveguide.

d. Boundary conditions.

(1) Energy is propagated down the waveguide in much the same manner as electromagnetic waves are transmitted in free space, except that these waves are confined within the metallic guide. However, when so confined, they will continue to be transmitted only if two conditions are satisfied. If these conditions, known as boundary conditions, are not met, the waves cannot be propagated down the waveguide.

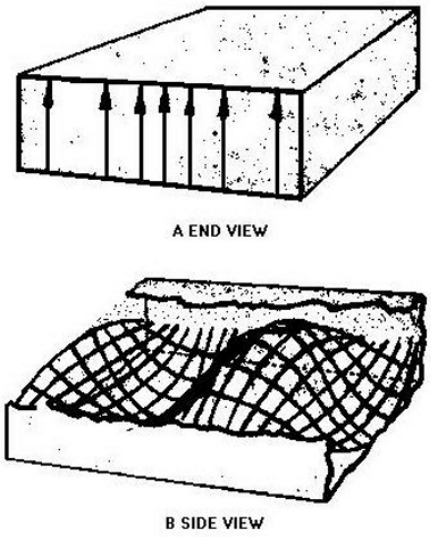


Figure 23. Half-sine wave E-field distribution.

(2) The first of these conditions is that an electric field must be perpendicular to the conductor if it is to exist at the surface of a conductor (fig 19). The converse of this condition is also true - an electric field cannot exist at the surface of a conductor if it has a component parallel to the conductor (assuming a perfect conductor). The second condition is that a varying magnetic field must exist in closed loops, parallel to the conductors, and perpendicular to the electric field. If a system meets one boundary condition, it also meets the other; thus, it is necessary to check for only one condition to determine whether a wave can exist at the surface of a conductor.

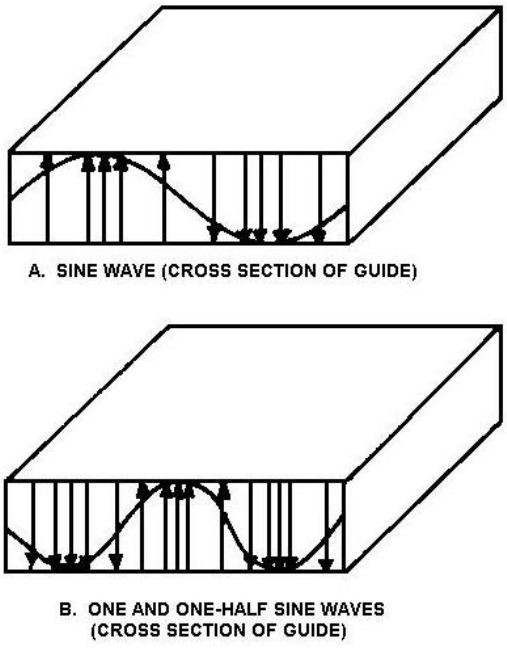


Figure 24. Other E-field distribution in waveguides.

(3) Figure 20 shows what happens when an electromagnetic wave is radiated from an antenna and confined between two parallel plate conductors. The electric field (E) lines are perpendicular to the conductors and the field varies sinusoidally along the distance between the plates. A varying magnetic field accompanies the varying electric field between the two parallel plates. The magnetic field must exist in closed loops and be parallel to the conductors (fig 21).

e. Wave patterns in a rectangular waveguide.

(1) The most common type of waveguide has a rectangular cross section, as shown in figure 22, where the dimension marked A indicates the vertical walls and dimension B the horizontal walls.

(2) A waveguide can accommodate many different electric field configurations. The field in figure 23 exists because there are no electric field lines parallel to the sidewalls. Although the electric field may terminate on a waveguide wall, no parallel component of the field can exist at a waveguide wall if the energy is propagated down the line. This means that the electric field must be zero at the sides of the waveguide. The proximity of the lines of force to each other is an indication of the strength of the electric field at that point. With the electric field moving continuously, the regions of maximum voltage move down the guide. The density of the electric field along the center of the guide increases and decreases sinusoidally.

(3) An electric field, called a full-sine wave field, can also exist in the rectangular guide because the E field is zero at the sidewalls (A, fig 24). In this example, the electric field lines change their intensity and direction in a sine wave pattern. Similarly, a one and one-half sine wave can exist in the rectangular guide because this field also meets the boundary conditions (B, fig 24). The E field is perpendicular to any conducting surface it touches and is zero along those surfaces to which it cannot be perpendicular.

(4) The magnetic field in a rectangular waveguide exists in closed loops parallel to the surface of the conductor. Its strength is proportional to the rate of change of the electric field. Figure 25 shows the magnetic field (H lines) that accompanies a half-sine wave electric field distribution. The intensity of the magnetic field varies sinusoidally down the center of the guide just as the electric field does.

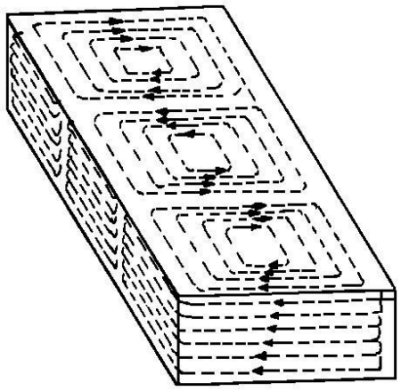


Figure 25. Magnetic field pattern.

(5) For the simplest mode of transmission in a rectangular guide, the energy is introduced into the guide by a quarter-wave antenna or probe. The probe, placed in the center of the B wall, radiates circular wave fronts in all directions. The wave front moves out from the antenna with horizontal H lines and vertical E lines.

f. Wave propagation.

(1) The development of wavefronts. When a small antenna is placed in the waveguide and excited at a radiofrequency both positive and negative half-cycles of energy are radiated in all directions as shown in figure 26. The initial wavefront produced is like an expanding circle traveling in all directions, however the energy traveling in the direction of arrows A and B of figure 26 will be reflected from the side walls. This reflected energy will distort the initial wavefront and produce a resultant wave which appears to be two wavefronts, each traveling at an angle to the sidewalls and reflected back and forth between them. Figure 27 shows a three-dimensional representation of two such waves and their relationship to each other. It should be noted that the two waves will cancel each other at the edge or sidewall.

(2) Path of wavefronts in a waveguide. If you could look through the top wall of the waveguide, you would see the wavefronts as indicated in figure 28. The solid lines represent the positive cycle of the waves (crest) and the broken lines represent the negative cycle of the waves (trough). The perpendicular distance between crests is the wavelength (λc) of each zigzag wave. λg is the wavelength of the resultant wave in the waveguide. The angle ϕ at which the wavefront strikes the sidewall is a function of the wavelength λc and the cross-sectional dimension (B wall) of the waveguide. It can be shown from figure 28 that the following relationship between the b wall and λc exists. $\text{Cos } \phi = \lambda c/2b$. It should be noted that if the frequency is decreased until the wavelength λc is equal to 2 times the b wall then $\text{Cos } \phi = 1$ and ϕ equals zero degree and the zigzag waves bounce back and forth perpendicularly to the guide walls. At this frequency, all the energy travels back and forth across the guide and none of it travels along the guide. This is the cutoff condition. When the wavelength is larger than twice the distance of the b wall no energy is propagated along the guide, shorter wavelengths or higher frequencies will be propagated as the zigzag waves down the guide.

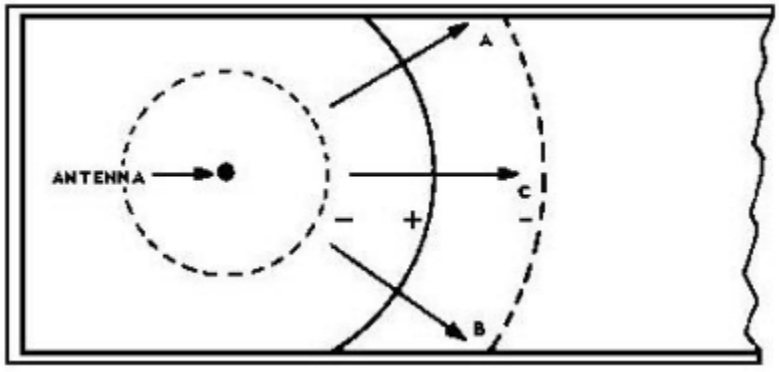


Figure 26. Radiation of energy in a waveguide.

Figure 27. Three-dimensional representation of two waves propagated in zigzag fashion.

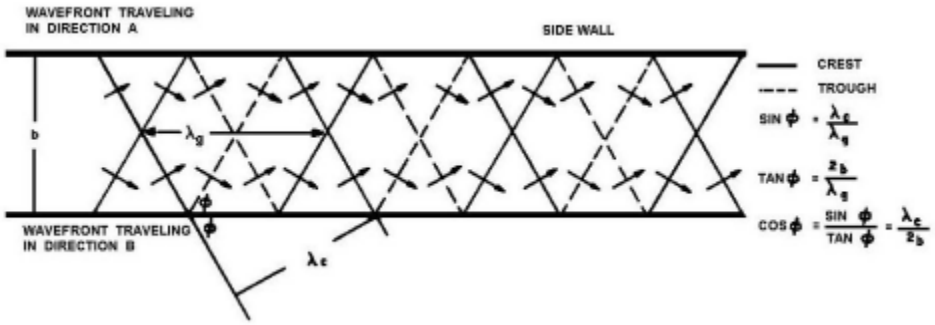


Figure 28. Paths of wavefronts in waveguide.

g. Group and phase velocity.

(1) Normally, energy traveling in free space is considered to be traveling at the speed of light. The energy traveling down the waveguide is in a zigzag path and it takes the energy longer to go from one end of the waveguide to the other end. The speed at which this energy travels down the waveguide is called the group velocity, and it appears to be slower than the speed of light or energy in free space.

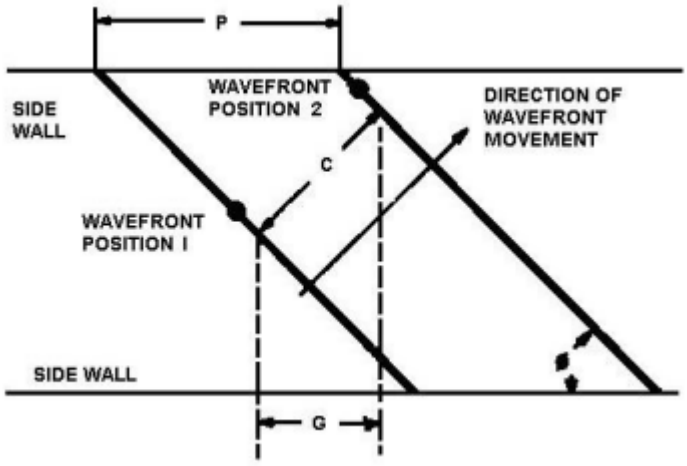


Figure 29. Relation of group, phase, and wavefront velocity.

(2) There is another velocity in the waveguide called phase velocity. This is the velocity of the resultant wave along the waveguide axis. The resultant wave is produced by the addition and cancellation of the criss-crossed wavefronts. The phase velocity appears to be traveling faster than the speed of light.

(3) Figure 29 shows a single wavefront of energy in a waveguide. The wavefront has moved from position 1 to position 2 in a given period of time. Let's consider the given period of time as being one cycle of energy. C is the distance traveled by the energy in free space at the velocity of light (V c). G is the distance traveled by the energy down the waveguide. This represents the group velocity (V g). Because of the diagonal movement of the wavefront, the group velocity is much less than the velocity of light.

(4) P is the distance the wavefront has traveled along the waveguide wall and represents the phase velocity (V p). Notice how much greater it is than the speed of light. The phase velocity is an apparent velocity and it appears to be greater than the speed of light because it has traveled a greater distance in the same period of time. In distance P, the energy in the waveguide has changed phase. That is why it is called phase velocity.

(5) It should also be noted that if the frequency is increased, the reflection angle ϕ will increase thus causing the group velocity to increase and the phase velocity to decrease.

h. Modes of operation.

(1) The shape, or pattern, of the electric and magnetic fields in a waveguide is determined by the frequency of the input signal and the size of the waveguide. (The shape, or pattern, will be called field configuration.)

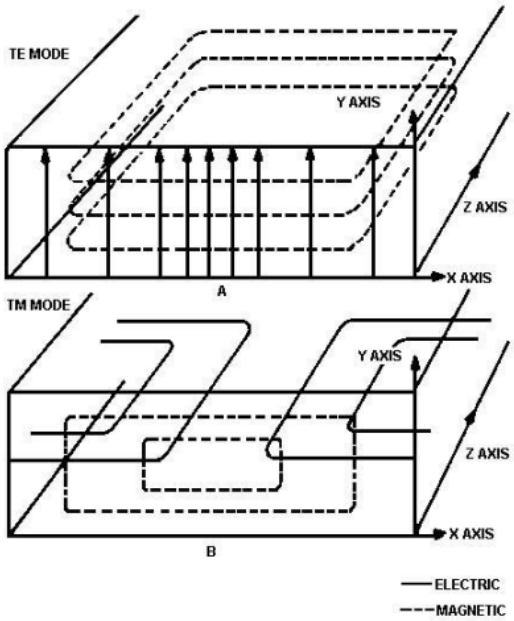


Figure 30. TE and TM modes.

(2) The different field configurations are known as modes. The mode is identified by the field that is perpendicular, or transverse, to the direction of propagation. The two main classes of modes are the transverse electric (TE) and the transverse magnetic (TM).

(3) In a TE mode, all components of the electric field lie in a plane that is transverse, or perpendicular, to the direction of propagation, as shown in figure 30, A. The direction of propagation is along the Z-axis. The distribution of the electric field is along the X-axis or along the width of the waveguide, and it is parallel to the Y-axis. The magnetic field is parallel to the X and Z-axes. The mode there is a TE, or transverse electric, mode.

(4) In a TM mode as shown in figure 30, B, the magnetic field is parallel to the X and Y axes but is also perpendicular to the Z axis or direction of propagation. The electric field is parallel to the X and Z-axes.

(5) To identify the different TE and TM modes which can occur, a system of subscripts is used. Two subscript numbers are used, such as TE m, n, TM mn, and so on. The first subscript, m, indicates the number of half-sine patterns of the transverse field that exists along the narrow side, or side a, of the waveguide. The second subscript, n, indicates the number of the half-sine patterns of the transverse field that exists along the wide side, or side b, of the waveguide. When there is no change in field intensity, the subscript 0 is used. Consider the TE mode shown in figure 30. There is no variation of the electric field along the Y-axis or the narrow side of the waveguide. The first subscript number is 0. A half-sine pattern of E lines does exist along the X-axes or wide side of the waveguide, so the second subscript is1. The field configuration or dominant mode is called a TE 0,1 mode.

(6) Now consider the TM mode also shown in figure 30, B. There is a half-sine pattern of H lines along the Y-axis and a half-sine pattern of H lines along the X-axis. The dominant mode now is TM 1,1.

(7) The TE 0,1 mode is most commonly used in radar and communications waveguides because it is most stable and requires the smallest waveguide dimensions for a given frequency.

i. Characteristic impedance. The characteristic impedance (Z o) of a waveguide depends upon several factors; e.g., the mode of operation, the width of the waveguide, the height of the waveguide, and the frequency of the signal. Thus, for a given mode of operation, any change in the height or width of the waveguide or in the signal frequency changes the impedance. By analogy, it would seem that since the E lines of the waveguides are parallel to the A walls, reducing the A dimension would shorten the E lines and thus increase the capacitance. This could be expected to decrease the characteristic impedance since capacitive reactance is inversely proportional to capacitance.

j. Standing waves in the waveguide. If the impedance of the load is not properly matched to the Z o of the waveguide, reflections occur in the same manner as in other transmission lines. These reflections result in standing waves which are detected by means of a probe in a slotted guide. Voltage maximums appear a half-wavelength apart as the probe moves down the center of the guide. The standing wave ratio is the ratio of the maximum voltage reading to the minimum voltage reading. A standing wave is just as objectionable in waveguides as in other lines and for the same reasons.

k. Power handling capabilities.

(1) The maximum power transmitted in a waveguide depends on the maximum electric field strength that can exist without breakdown. As the charge is built up between two conductors separated by air, a point is reached where the air (dielectric) breaks down and an arc-over occurs. The intensity of the electric field at this point is known as the electric field breakdown intensity or strength. If the electric field strength at any point in a waveguide exceeds this electric field breakdown strength, dielectric breakdown occurs. At this time, the microwave power is dissipated in the walls of the guide and the arc that results.

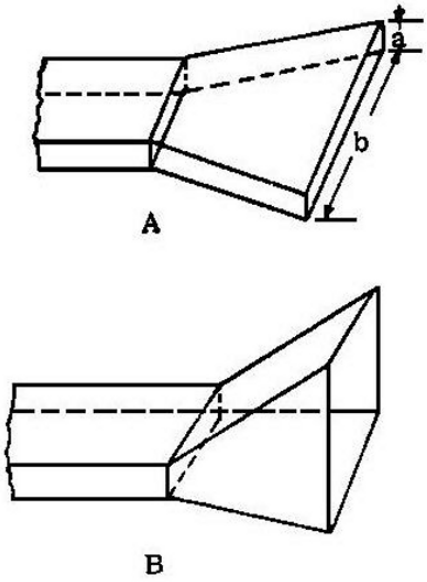


Figure 31. Radiating horns.

(2) The breakdown electric field strength of air varies with pressure, humidity, and temperature. For normal conditions, the value of the breakdown field is about 30,000 volts (peak) per centimeter. To increase the power handling capability of radar equipment, some components are pressurized.

l. Radiating horns.

(1) It would seem that just by opening the end of the waveguide, the wave would travel out in space. It would, if it were not for the impedance mismatch. The ratio of E field's density to H field's density in free space is such that the equivalent impedance is approximately 377 ohms. This is lower than the characteristic impedance of most rectangular waveguides. Consequently, there would be reflections in the line resulting in high line losses and poor power transfer. The impedances may be matched by employing an electromagnetic horn such as the sectorial horn in figure 31A. This horn not only matches the impedances by expanding the b dimension of the guide, but it also gives the radiation a more directive property. Ideally, the pitch of the horn should be very gradual, but a pitch of 40 degrees gives good results.

(2) The electromagnetic horn in figure 31B is expanded in both dimensions. It is used more often with a parabolic reflector because it distributes the energy more evenly over the surface of the reflector.

m. Coupling methods.

(1) Waveguide coupling. In a two-wire or coaxial line transmission system the generator is coupled to the line by the connection of its output terminals directly to the line conductors. This is not possible with waveguides because there are no comparable conductors to connect to the general terminals. Instead, the generator energy must be transformed into an electromagnetic wave by means of an element that acts as an antenna. This is the method of coupling the generator energy into the guide. Similarly, at the output end of the guide, the electromagnetic energy must be extracted from the guide. This is known as coupling energy out of the guide.

(2) Probe coupling.

(a) A coupling probe is a small metallic conductor that is inserted in the waveguide parallel to the lines of the electric field (fig 32). The impedance is matched by varying the depth of the probe inserted into the guide. This is often an operational adjustment.

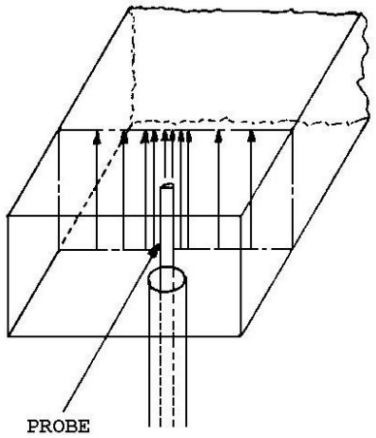


Figure 32. Probe coupling.

(b) Maximum coupling is obtained by inserting the probe at a point of maximum electric field intensity. If less coupling is desired, the probe is placed in the guide where the electric field is less intense. More or less coupling may also be obtained by varying the length of the probe. Usually, the probe is made about a quarter-wavelength long so that its action is somewhat similar to that of a quarter-wave antenna.

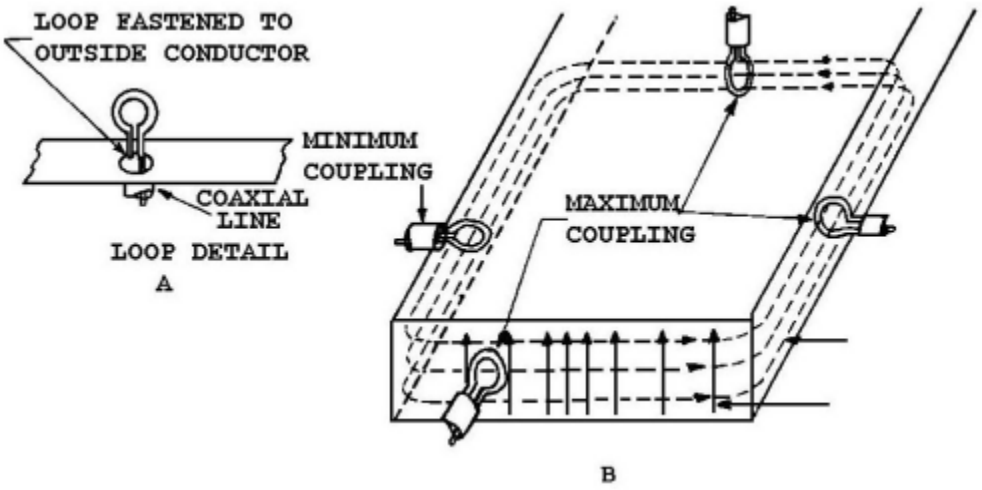


Figure 33. Orientation of the coupling loop.

(3) Loop coupling.

(a) Another method of coupling energy into or out of a waveguide is by means of a coupling loop. A loop of wire, a half-wave in length, has similar properties to a parallel resonant circuit and will radiate energy. In figure 33 the loop is placed in the waveguide in such a position that the magnetic field (H) lines are perpendicular to the loop's plane. The voltage induced in the loop is directly proportional to the number of magnetic flux lines that cut it.

(b) To extract maximum energy from the guide, or to insert energy with maximum efficiency, the loop is placed at a point of maximum magnetic field intensity. If less coupling is desired, the loop is rotated so that fewer magnetic lines link it. When the loop is rotated 90 degrees from the maximum coupling position, no magnetic lines link the loop. This position results in minimum coupling. Moving the loop to a point of less magnetic field intensity or controlling the depth of penetration are other methods of varying the coupling.

(4) Windows, iris, or slot coupling.

(a) Apertures, or windows, are sometimes used to couple energy from one waveguide to another. This is very practical if the two sections are adjacent and separated only by the walls of the guide. If a hole is drilled in a waveguide, energy will usually be radiated through the hole. However, the amount of energy radiated varies considerably with the location of the hole (fig 34).

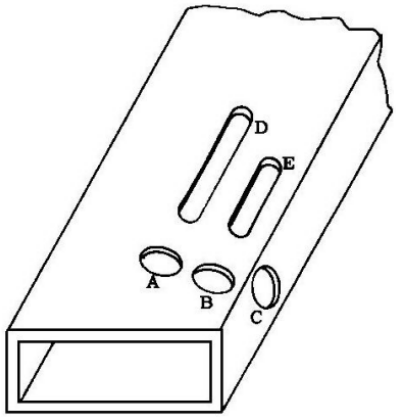


Figure 34. Apertures located in various parts of a waveguide.

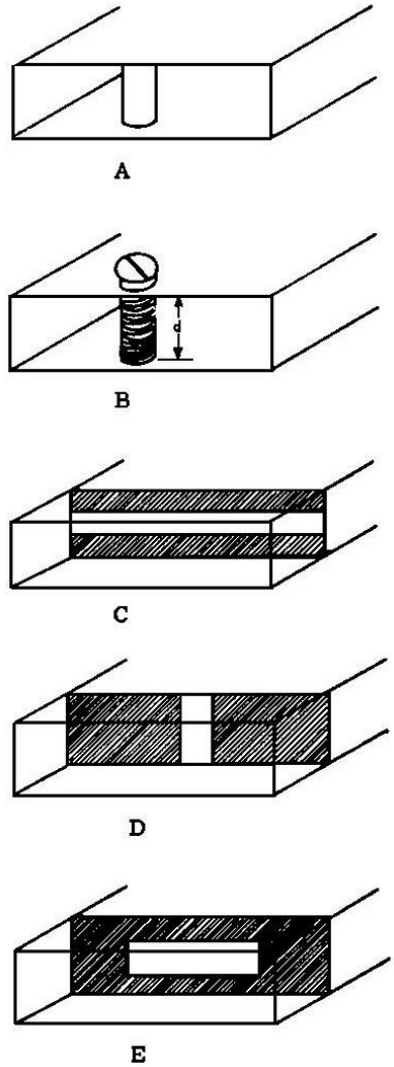


Figure 35. Reactive devices.

(b) To correctly predict the amount of radiation from an aperture, it is necessary to know the pattern of the E and H fields in the guide and the current distribution in the walls.

(c) A probe, for measuring the standing wave ratio, is often introduced through a longitudinal slot in the center of the B wall. This is because a negligible amount of energy is radiated from this location. However, longitudinal slots in the A wall, or transverse slots in the B wall, interrupt many current paths and radiate large amounts of energy.

n. Impedance-matching techniques.

(1) General. When energy is coupled into or out of a waveguide, there should be a proper impedance match between the generator, the coupling elements, the waveguide, and the load. In this respect, the waveguide acts exactly like a two-wire line and follows the same principles discussed in paragraph 3j. In other words, unless the waveguide is terminated in its characteristic impedance, standing waves will be created. Generally, appropriately matched elements, such as impedance-matching transformers and reactive elements, effect maximum transfer of energy.

(2) Reactive screws.

(a) A shunt reactance can be injected in a waveguide by inserting a metallic element that may be cylindrical in shape or in the form of a strip. When this element extends across the full height of the guide (fig 35A), it is called an inductive post. When the element is in the form of a screw (fig 35B), whose insertion can be varied, it is called a tuning screw.

(b) The reactance obtained by a tuning screw varies with the depth of insertion d. As the screw extends into the guide, currents set up in the screw cause reflections in the guide. When d is small the screw acts as a shunting capacitance. Increasing d increases the shunting capacitance until d is equal to a quarter-wavelength. At this point resonance occurs and the reactance is zero. For greater values of d the screw becomes inductive. Therefore, it can be thought of as a quarter-wave antenna that reflects capacitance if cut too short or inductance if cut too long.

(3) Reactive irises.

(a) Another method of obtaining a shunt reactance is to place metal strips or partitions in the guide at right angles to the direction of energy propagation. If a partition is placed in the guide, with a slit parallel to the B walls (fig 35C), reflections occur which give an effect equivalent to placing a parallel capacitance across the line. This reduces the A dimension of the guide and thus reduces its power handling capacity. As the power is increased, an arc usually appears across the narrow dimension of the slot. For this reason it is more common to use the inductive iris (fig 35D), which is similar to the capacitive iris except that the slot is parallel to the A walls of the guide. Since no E field exists between the A walls of the guide, the restriction in the guide will most probably not cause arcing.

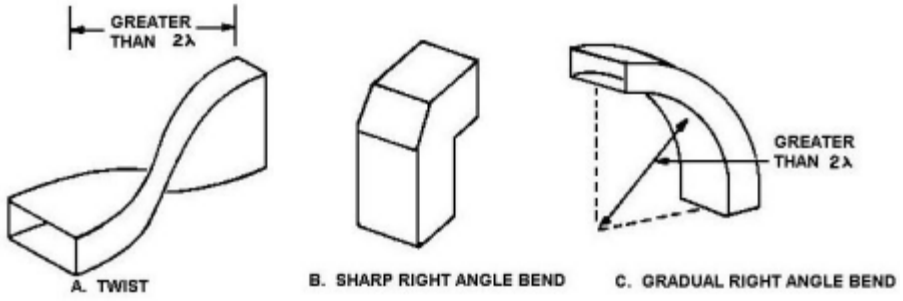


Figure 36. Waveguide bends and twists.

(b) When metallic elements are placed along all walls (fig 35E), there is both a shunt inductance and a shunt capacitance across the guide. This type of aperture, called a resonant window or diaphragm, is the equivalent of a parallel-tuned circuit. At the resonant frequency, the inductive reactance is equal to the capacitive reactance and the window represents a pure resistance.

o. Bends and twists.

(1) To prevent reflections in the waveguide, abrupt changes in the size or shape of the guide must be avoided. In some applications of microwave equipment, it is necessary to change the orientation of the waveguide as shown in figure 36A. The orientation of a waveguide is altered to change the polarization of the fields for matching purposes, or to accommodate a special type of load. To minimize reflections, the basic principles in a twisting waveguide is to make the change as gradual as possible.

(2) Several waveguide bends or elbows are used for making right-angle turns. One of these is the sharp right-angle bend, also called a corner, shown in figure 36B. Another is the more gradual bend (fig 36C). In the sharp bend the top wall of the guide is beveled to minimize reflection. In the more gradual bend reflections are minimized by making the radius of the bend at least two wavelengths long. This gradual change produces a very small mismatch and therefore reduces reflection losses.

p. Flexible waveguides.

(1) In some applications a flexible, rectangular waveguide is required. It may be used for slight bends between two fixed guides or it may be used for twist and bend applications. Some common types of flexible guides are shown in figure 37.

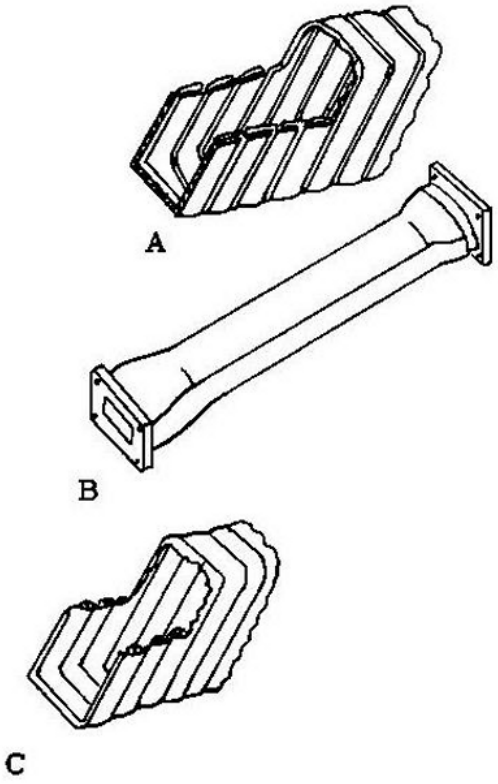


Figure 37. Flexible waveguide.

(2) The type shown in figure 37A is constructed of crimped, spirally wound, strips of silver-coated brass. When the guide is flexed, the stripes slide over one another and maintain contact. Figure 37B shows a similar section of rubber-covered guide with flanged connectors soldered to the ends. The rubber covering seals the guide so that it may be pressurized as well as serving as a mechanical protection. Figure 37C is another spirally constructed guide, differing from that in figure 37A in that each strip is crimped tightly to the next so that slippage is impossible. This guide is flexed by bending the thin walls of the corrugated metal.

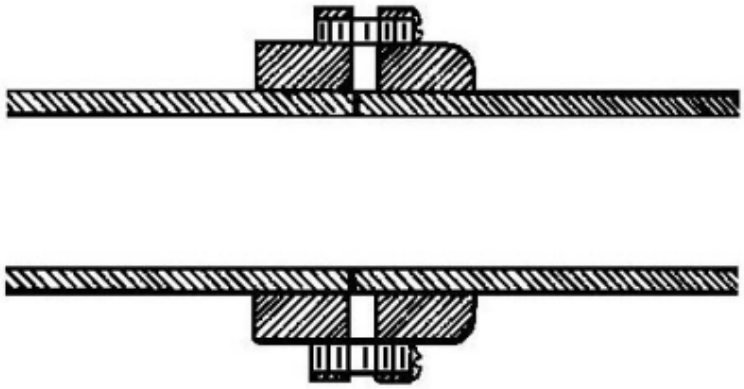


Figure 38. A contact joint.

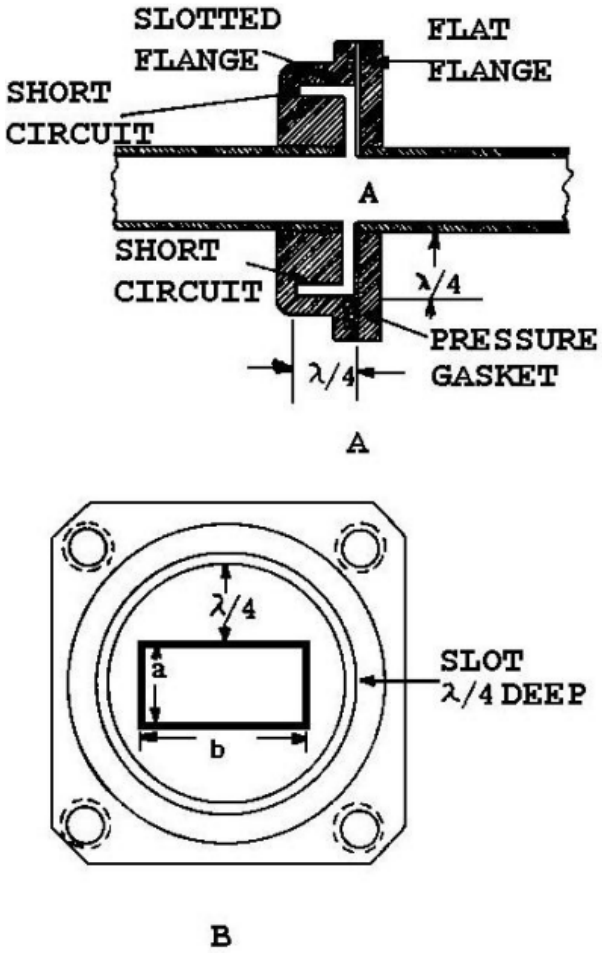


Figure 39. A choke-flange joint.

q. Joints in waveguides.

(1) Waveguides are constructed in sections, fitted with flanges soldered to the ends of the guide, and then bolted together. These flanges are basically of two types: the contact flange and the choke flange. The simplest way of connecting two sections is the flange-to-flange or contact method. In order to assure good electrical contact, the joined surfaces must not be corroded. The contact flange is preferred for precision equipment that is not subjected to rough treatment or frequent disassembly. Figure 38 shows that there is no break in the guide wall at the joint. The joint's efficiency is affected by the connection's tightness and the accuracy of end surface machining.

(2) The choke flange (fig 39), which does not require precise alinement, is favored for most assemblies. It provides a good electrical microwave connection between waveguide sections and does not require contacting metal surfaces. A longitudinal cross section is shown in figure 39. The distance from the high voltage point, in the center of the B wall, to the slot is a quarter-wavelength. Since the slot's depth is also a quarter-wavelength, energy leaving the guide through the aperture at A is reflected from the short circuit, a half-wavelength distant. This reflection results in a low impedance across the gap at A, which is lower than that normally obtained by a metal-to-metal contact. Figure 39B shows an end view of the flange.

(3) Since the antenna assembly in radar scanning is often rotated continuously, the transmission line may require a rotary joint. It is also necessary that the polarization of the radiated wave be the same for all positions of the antenna. To permit one section of a cylindrical waveguide to rotate with respect to the other, a choke joint of the wabble type can be used (fig 40). As was discussed previously, no actual mechanical contact is needed in this type of joint; instead, the electrical connection is made because of the low impedance existing between the two sections of waveguide.

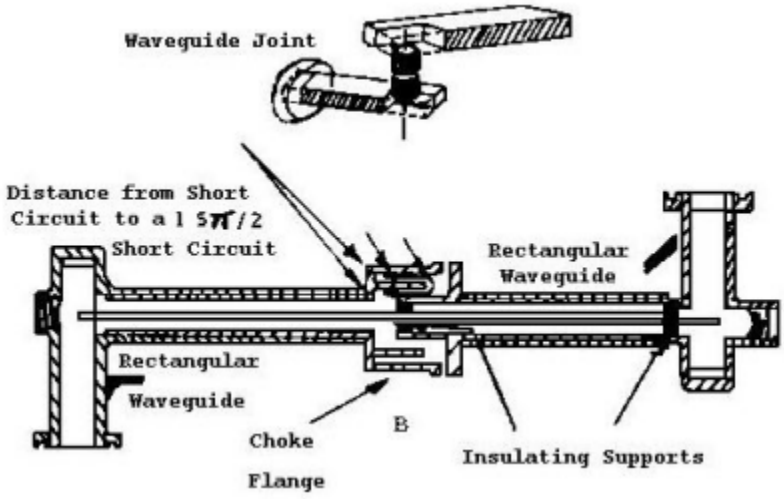


Figure 40. Rotary joint using coaxial line section with choke joint.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 6

1. The formula for the characteristic impedance (Z o) of a transmission line is

   A. $\sqrt{LC}$

   B. $\sqrt{L/C}$

   C. $1/\sqrt{LC}$

   D. $1/\sqrt{L/C}$

2. Which transmission device is MOST effective at frequencies above 1,000 MHz?

   A. Waveguide

   B. Coaxial line

   C. Slotted line

   D. Artificial line

3. What ratio is MOST essential for maximum power transfer?

   A. Z o of generator is equal to two times Z o of transmission line

   B. Z o of transmission line is equal to Z o of generator

   C. Z o of load is greater than Z o of transmission line

   D. Z o of generator is equal to one-half the Z o of the load

4. What is an advantage of a coaxial transmission line?

   A. Low cost of construction

   B. Low frequency application

   C. Minimum radiation losses

   D. Minimum insulation losses at high frequencies

5. What is a disadvantage of waveguides?

   A. Difficult to match

   B. High skin-effect loss

   C. Difficult to install

   D. High dielectric loss

6. Which of the following types of line is not a transmission line?

   A. Two-wire line

   B. Coaxial line

   C. Load line

   D. Twisted pair line

7. What indicates perfect matching between the signal line and the input and output impedance?

   A. Maximum line reflections

   B. Minimum load absorption

   C. No reflected waves

   D. No refracted waves

8. What MAINLY determines the velocity factor of a transmission line?

   A. Polarization of the line

   B. Characteristics of the dielectric material

   C. Polarization of the antenna

   D. Characteristics of the resistive material

9. What is the ratio of maximum voltage to minimum voltage on a transmission line called?

   A. Energy ratio

   B. Flat-line ratio

   C. Pulse ratio

   D. Standing-wave ratio

10. The two wavefronts in a waveguide

   A. are always perpendicular to each other.

   B. are not affected by input frequency.

   C. are maximum at the center of the waveguide.

   D. occur when the standing wave ratio is 1:1.

11. When a transmission line is terminated in a short circuit, what standing wave of voltage and current exists at the short?

   A. Maximum voltage and minimum current

   B. Maximum current and maximum voltage

   C. Minimum voltage and maximum current

   D. Minimum current and minimum voltage

12. What is the standing wave voltage amplitude three-quarters of a wavelength from a shorted line termination?

   A. Three times that of the line incident wave

   B. Equal to that of the incident wave

   C. One-half that of the incident wave

   D. Twice that of the incident wave

13. What impedance is presented three-quarters of a wavelength from an open line termination?

A. Minimum

B. Maximum

C. Inductive

D. Capacitive

14. Inside the waveguide, the

A. E lines have maximum amplitude at the sidewall.

B. E lines and H lines are parallel to the sidewall.

C. magnetic lines exist in closed loops.

D. electromagnetic energy is spherical in shape and travels down the center of the guide.

15. What type stub is used to cancel a capacitive transmission line reactance?

A. Capacitive

B. Inductive

C. Series

D. Resistive

16. What are matching line sections?

A. Connectors between lines of equal characteristic impedance

B. Antennas between lines of equal length

C. Antennas between lines of unequal length

D. Connectors between lines of different characteristic impedances

17. A coupling probe is

A. used to control the dominant mode in a waveguide.

B. a metallic insulator used to support a coaxial line.

C. a half-wave radiator.

D. used to extract energy from a waveguide.

18. At what frequency do waveguide losses become too great for practical use?

A. Resonant

B. Saturation

C. Cutoff

D. Synchronized

19. Which is a boundary condition of a waveguide?

A. E field must be parallel to the conductor

B. H fields are in closed loops and parallel to the E field

C. E field must be perpendicular to the conductor

D. H fields are in open loops and parallel to the electric field

20. What happens if the signal frequency in a waveguide is increased?

A. The incident angle becomes constant

B. The group velocity increases

C. The reflected angle decreases

D. The group velocity becomes constant

21. What BEST describes a transverse electric mode?

A. The electric field components are parallel to the direction of propagation

B. The magnetic lines are perpendicular to the direction of propagation

C. The magnetic lines are parallel to the direction of propagation

D. The electric field components are perpendicular to the direction of propagation

22. Which formula is used to calculate wavelength?

A. (Lambda) λ = velocity/frequency

B. (Lambda) λ = frequency/velocity

C. (Lambda) λ = acceleration/frequency

D. (Lambda) λ = frequency/acceleration

23. How can a waveguide's power handling capability be increased?

A. By pressurizing certain components

B. By depressurizing certain components

C. By reducing the size of the A walls

D. By reducing the size of the B walls

24. How is proper impedance matching accomplished in probe coupling?

A. By varying the diameter of the probe

B. By varying the depth of the probe inserted in the guide

C. By varying the point of probe insertion in the guide

D. By varying the length of the probe

25. What is the function of a tuning screw?

A. Modulation

B. Impedance coupling

C. Attenuation

D. Impedance matching

LESSON 7. ANTENNAS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the description, principles of radiation, function, and use of basic antennas.**
Lesson Credit Hours.....	**Three**

TEXT

1. INTRODUCTION.

a. History. Our background of electromagnetic waves dates from about 1873 when the Scottish physicist, J. C. Maxwell, published his papers on "Electricity and Magnetism." Maxwell explained all the known magnetic and electric phenomena on the basis of a substance called ether, which he assumed to fill all space. Electric and magnetic fields were stressed in this medium, and light waves as well as other electromagnetic waves were motions of the ether. The ether hypothesis has long since been abandoned, but Maxwell was correct in his belief that these waves were electromagnetic in nature. The chief use of these electromagnetic waves has been in the field of communications. Beginning with Marconi and his wireless telegraph in 1895, electromagnetic waves have become increasingly important as a medium of communication in the fields of radiotelephony, news and entertainment broadcasting, and in radar. The greatest contribution of Marconi to the new science was his invention of the antenna, or aerial as he called it.

b. Function of the antenna. An antenna is an electronic device that is used for radiating electromagnetic energy into space or for collecting electromagnetic energy from space. In the radar transmitter the magnetron generates the high frequency signal, but an antenna is needed to change this signal into electromagnetic fields which are suitable for propagation into space. The radar receiver will amplify any signal that appears at its input terminals, but an antenna is required to intercept the electromagnetic fields in space and convert them into a voltage that the receiver can interpret.

2. CHARACTERISTICS OF ANTENNAS.

a. Antenna reciprocity. Fortunately, separate antennas are seldom required for transmitting and receiving radio energy. Normally, any antenna transfers energy from space to its input terminals as efficiently as it transfers energy from the output terminals into space, assuming, of course, that the frequencies are the same. The ability of an antenna to both transmit and receive is known as antenna reciprocity; it is possible chiefly because antenna characteristics are essentially the same whether an antenna is sending or receiving
electromagnetic energy.

b. Directional properties.

(1) Usually, the most important characteristic of a radar antenna is its directional property, or its directivity, which means that an antenna radiates more energy in one direction than in another. For that matter all antennas are directional, but some are more so than others. Radar antennas are usually highly directive in order that the maximum electromagnetic energy generated by the transmitter will strike an object in a given direction. In other systems it may be desirable for the energy to be radiated equally well in all directions.

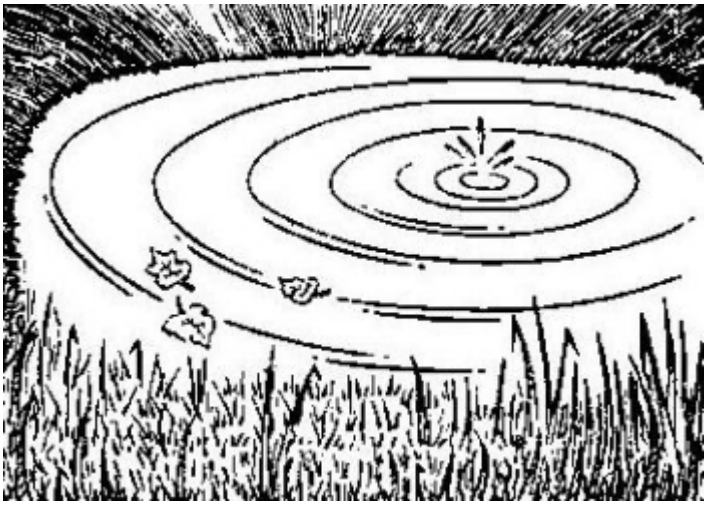


Figure 1. Wave motion in pond.

(2) An example of a radar antenna system that radiates energy in a given direction is the airborne navigation and bombing set. In this set, only a limited amount of power is available at the transmitter. In order to achieve maximum benefit from this minimum power, all of the power is sent in the same direction. Since this antenna is also used for reception, it likewise receives electromagnetic energy from only one direction. Because of design features it is possible to detect the direction of an object toward which the antenna is sending and receiving energy. The physical position of the antenna indicates the direction of the object.

(3) An example of a nondirectional radar antenna is the antenna installed in the radar beacon. This antenna must receive energy equally well from all directions, so that a radar-equipped airplane can ascertain its position regardless of its direction from the beacon antenna.

c. Antenna efficiency.

(1) An efficient antenna is one that wastes very little energy. The higher the antenna efficiency, the lower the energy loss. The greatest cause of decreased antenna efficiency is the loss of energy in the form of heat during conversion of RF energy into electromagnetic energy.

(2) Actually, antenna efficiency may be as great as 90 percent in a single antenna element. An entire antenna system, properly designed, can concentrate all of its radiated energy in a given direction with very little being lost in other directions. A directional-receiving antenna is more sensitive to signals in a given direction than a similar nondirectional antenna is to signals in any direction. This greater sensitivity (which is another way of stating that there is less energy loss by the antenna) represents greater receiving ability and, accordingly, greater efficiency.

3. WAVE MOTION.

a. The movement of electromagnetic waves can be compared to the movement of waves on a pond. Suppose you are standing at the edge of a small pond of water and its surface is smooth and unbroken except for a few dead leaves floating near your feet. If you toss a stone into the center of the pond, ripples spread out in all directions, and, in a few moments, the disturbance reaches the leaves and they begin to bob up and down. As shown in figure 1, the energy imparted by the stone has made itself felt across the surface of the pond.

b. When the stone is tossed into the pond it sets up a disturbance at the place where it strikes the water. With the disturbance as the center, waves are produced which move outward in expanding circles. As each circle moves out toward the edge of the pond, a new one forms at the center. Eventually, the waves cover the surface of the pond and the leaves are bobbing up and down as each wave passes. Notice that the leaves are not carried along with the waves to the shore, but rather move up and down in place. This is because the water on which the leaves float is not moved sideways by the waves. The only effect of the wave is to raise or lower each particle in its path. The part of the wave that raises a particle is called the crest; the part that lowers a particle is called the trough.

c. The distance covered by the waves in a given time is a measure of the velocity or speed with which the waves travel across the pond. It can be expressed in miles per hour, centimeters per second, or any unit of distance per any unit of time. For our purpose it is expressed by this simple relationship:

$$\text{velocity} = \frac{\text{distance traveled}}{\text{time required to travel this distance}} \quad \text{or} \quad v = \frac{d}{t}$$

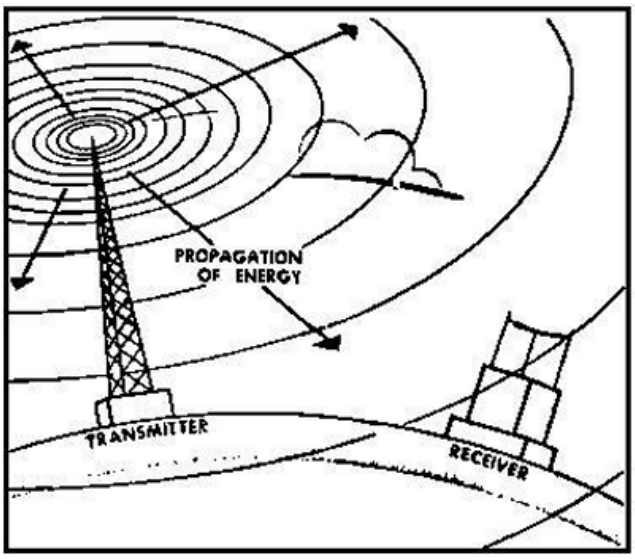


Figure 2. Electromagnetic wave motion in space.

4. ELECTROMAGNETIC WAVE MOTION.

a. Suppose that a source of RF energy, such as a radio transmitter, is connected to an antenna. The antenna sets up fields in the surrounding space and the resultant waves are propagated in all directions in the form of expanding concentric circles (fig 2). When these waves encounter some device, such as a receiving antenna, on which they can act, some of their energy is given up to that device. This energy is transferred through space to the receiver in much the same manner as the stone's energy was transferred through the water.

b. The velocity of these electromagnetic waves moving through space is found in the same manner as the velocity of the water waves. It is the distance divided by the time required to cover that distance. Instead of taking any distance, consider the distance from the crest of one wave to the crest of the next. This is the length of one wave, or one wavelength, that was previously calculated in lesson 6.

5. ELECTROMAGNETIC ENERGY IN SPACE.

a. A half-wave dipole antenna, the fundamental element in an antenna system, is used as the starting point for discussing the radiation of electromagnetic energy into space. Electrically, the dipole antenna acts like an open-circuited, quarter-wavelength, RF line which is excited by a generator. It appears to the generator as a resonant circuit. A dipole, consisting of a piece of wire cut in half and attached to the terminals of a high frequency AC generator, is illustrated in A of figure 3. The frequency of the generator is such that each half of the wire is one-quarter the wavelength of the generator output. Due to the resonant characteristics of this arrangement, high circulating currents flow in the antenna when it is excited by the generator. This current flow sets up two strong fields about the antenna: one the magnetic field (H), and the other the electric field (E). However, due to the U-shape of the antenna and the fact that the currents in each wire move in opposite directions, the H- and E-fields are in opposition and cancel. Therefore, the overall field strength of the antenna assembly is very low.

b. However, suppose that the two wires are moved as far apart as possible (B, fig 3). In this case, the current flow in each wire is in the same direction. The resulting E- and H-fields will now aid rather than oppose each other and create strong fields about the antenna. The distribution of E- and H-fields is illustrated in C and D, figure 3.

c. B, figure 3, shows the distribution of current and voltage around an antenna, with the current and voltage represented by the dotted and solid lines respectively. Note that the current is maximum at the center and zero at the ends, while the voltage is maximum at the ends and zero at the center. The magnetic field is greatest where the current is greatest (C, fig 3), and the electric field is strongest at the outer ends (D, fig 3).

d. The fields associated with the energy stored in the antenna, or resonant circuit, are called the induction fields and decrease with the square of the distance from the antenna. They are, however, only local in effect and play no part in the transmission of electromagnetic energy. These induction fields represent only the stored energy in the antenna and are responsible only for the resonant effects which the antenna reflects to the generator.

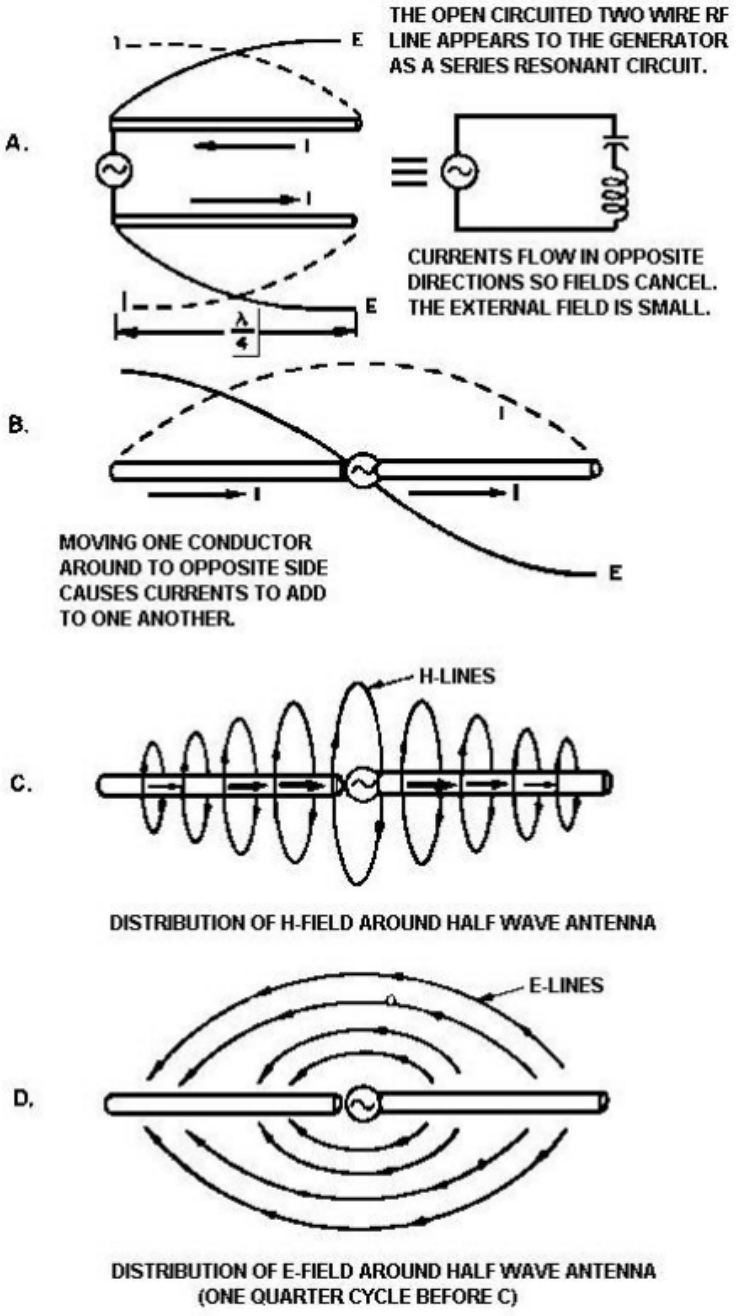


Figure 3. Development of half-wave antenna from λ/4 open-ended line.

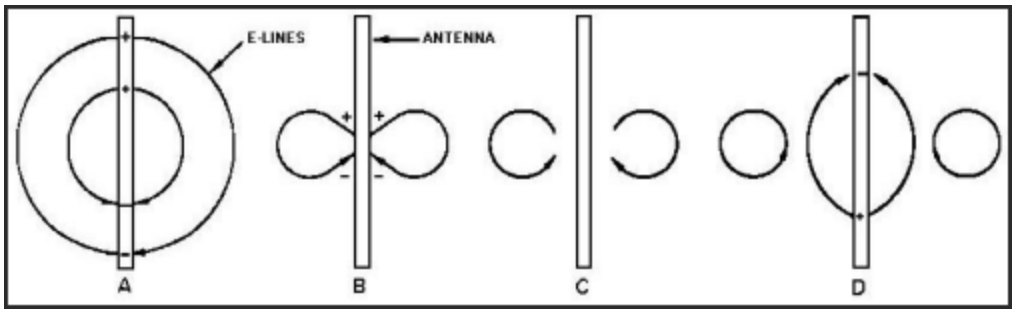


Figure 4. E-field detaching itself from an antenna.

e. The fields set up in the transfer of energy through space are known as the radiation fields. Although these fields decrease with the distance from the antenna, this decrease is much less rapid than the decrease of the induction field. The radiation field, decreasing at a linear rate rather than the square of the distance, will reach great distances from the antenna.

6. RADIATION OF FIELDS.

a. A current alternating at a radiofrequency and flowing in a wire of finite length can produce electromagnetic fields. These fields may be disengaged from the wire and set free in space. The method of setting these waves free is discussed in this section. Figure 4, a simple illustration of an E-field detaching itself from the antenna, is one explanation of field radiation. At A, the E-field is maximum and the outer E-lines are stretched away from the inner ones. This is due to the repelling force between the lines of force. As the voltage decreases toward zero, the radiation field decreases and the E-lines retract back into the conductor. If the voltage decreases slowly, the entire field will collapse back into the conductor. On the other hand, if the decrease of voltage is rapid, the outer parts of the field cannot move in very fast; therefore, they exist around the conductor as a relatively large E-field when the voltage is almost down to zero (B, fig 4). At C, figure 4, the voltage has decreased to zero and the remaining E-field has nothing left to support it. At this time (D, fig 4), the voltage again begins increasing and a new E-field starts developing around the antenna, which will push the original E-field away. The action of one field pushing away the preceding field is analogous to the snapping of a whip in that a part of the E-field is snapped off the antenna with each cycle. The snapped-off field is projected into space and moves away from the antenna at a constant speed of 186,000 miles per second.

b. The ease by which radiation occurs is dependent upon the frequency applied. At lower frequencies, such as a 60 HZ power frequency, voltage on the antenna changes so slowly that the component of energy radiated is extremely small and of no practical value. At higher frequencies, such as 50,000 HZ and up, the radiated energy is great enough to meet communications requirements.

7. FIELDS IN SPACE.

a. Figure 5 indicates the manner in which radiation fields are propagated from the antenna. The E- and H-fields are shown as separate sets of flux lines about the antenna. The electric flux (E) lines are the closed loops on each side of the antenna. The magnetic flux (H) lines are closed, circular loops that have their axes around the antenna. In other words, the antenna is the center of each loop. The sine waves, labeled the curves of radial variation of flux density, indicate the relative field strength at various distances and angles from the antenna. Since the field configuration is a traveling wave phenomenon, rather than a standing wave, the magnetic and electric fields are in phase; therefore, the sine waves apply to the flux density of either field.

b. In the directions perpendicular to the axis of the antenna, both the H- and E-fields are strong. In the directions parallel to the axis of the antenna, or off the ends, no H-field, and only a very small E-field, is formed. Hence, the flux density is very small off the ends of the antenna. In other words, due to the directional properties of the half-wave antenna, most of the radiated energy travels in directions perpendicular to the antenna but very little in directions along its axis.

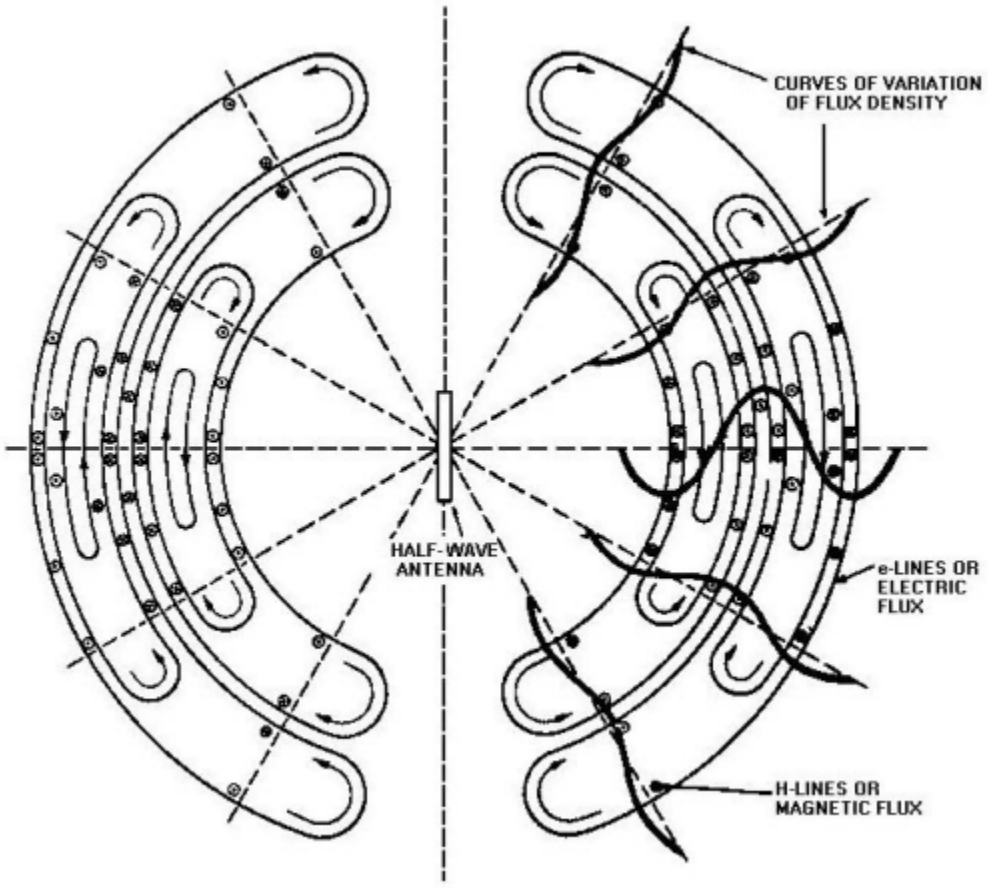


Figure 5. Radiation field expanding radially from a dipole antenna.

c. As explained in lesson 6, no moving E-field can exist without an H-field; conversely, no H-field can be propagated without an associated E-field. Similarly, with the propagation of electromagnetic energy into space, no moving electrostatic forces can exist without magnetic stresses existing in space, and no magnetic force in motion can exist without an electrostatic stress. Each one creates and is necessary for the existence of the other.

8. INTRODUCING ENERGY TO THE ANTENNA.

a. General. Although energy may be fed to an antenna in a variety of ways, most antennas are voltage fed or current fed as shown in figure 6. When the excitation energy is introduced to the antenna at the point of high circulating currents, the antenna is current fed. Likewise, when the energy is introduced at the point of maximum voltage, the antenna is voltage fed. RF transmission lines usually carry the energy from the generator to the antenna since it is seldom possible to connect a generator directly to the antenna. The RF lines which carry the excitation energy might be resonant lines, nonresonant lines, or a combination of both.

b. Feeding antennas with resonant lines.

(1) In a voltage-fed, half-wave antenna, which is excited by a resonant RF line, the end of the antenna is connected as shown in figure 7. Voltage changes at the connection point excite the antenna into oscillation. The impedance at the end of the antenna is high, since the voltage is high and the current is low. The RF line (fig 7) is a half-wavelength, two-wire line. The characteristic impedance of such a line is usually low in order that standing waves may be set up by the high impedance at which the line is terminated. The line must always be a multiple of quarter-wavelengths, so that it acts like a resonant circuit and provides a high impedance input. Small irregularities in line lengths can be compensated for by tuning the input parallel resonant circuit.

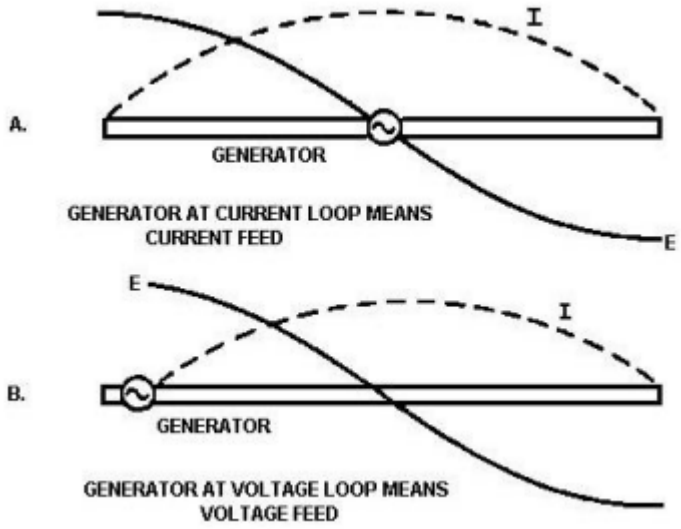


Figure 6. Current and voltage feed.

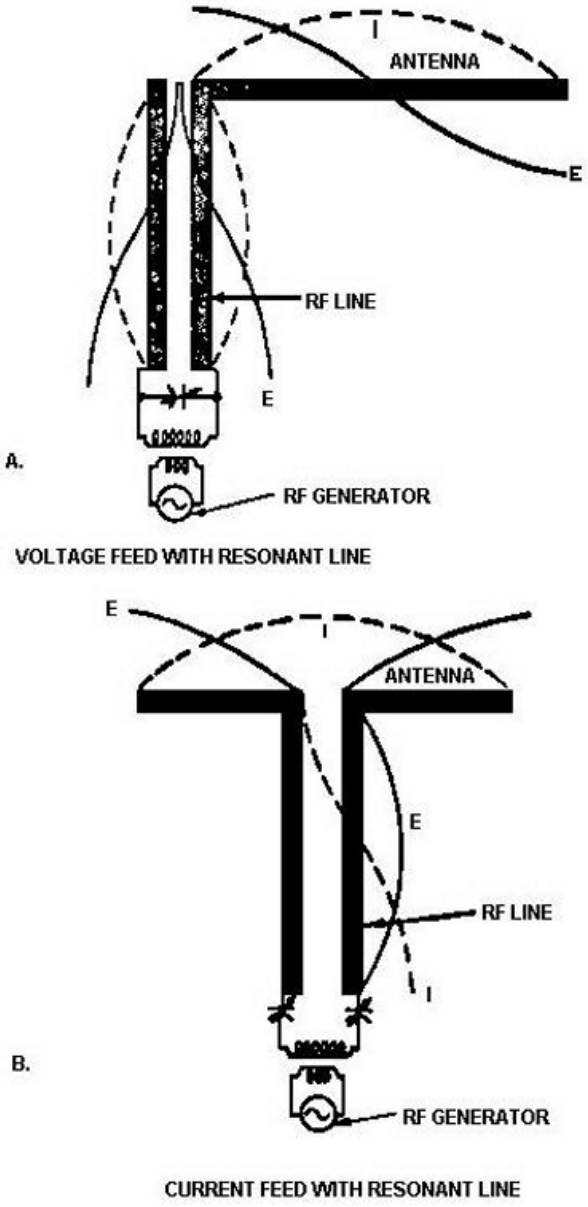


Figure 7. Feeding antennas with resonant lines.

(2) Referring to figure 7B, the current-fed antenna with a resonant line is connected to the center of the antenna. This antenna has a very low impedance at the center and, like the voltage-fed antenna, has standing waves. Making the line exactly a half-wavelength causes the impedance at the sending end to be low; therefore, a series resonant circuit is used to develop the high current necessary to excite the line. Adjusting the capacitors at the input compensates for irregularities in the line length.

(3) Although these examples of feeding antennas are simple ones, the principles described apply to all antennas and to lines of any length providing that both are of resonant length. The line connected to the antenna can be a two-wire line, a coaxial line, or a waveguide. In radar equipment, the coaxial line or waveguide is preferred.

(4) One advantage of the resonant line is that matching devices are unnecessary. In addition, incorrect antenna lengths can be compensated for by transmitter tuning. Its disadvantages are increased I^2R losses due to high standing waves of current, increased possibility of arc-over between lines, critical lengths, and production of radiation fields. Radiation fields are undesirable because they distort the normal radiation pattern of the antenna.

c. Feeding antennas with nonresonant lines.

(1) Figure 8 illustrates the different methods of exciting a half-wave antenna using nonresonant lines. The input to the center of the antenna in A, figure 8, is 73 ohms and the characteristic impedance of a coaxial cable is 73 ohms. Therefore, the most common method of feeding this antenna would be by coaxial cable connected directly to the center of the antenna. This method will produce no standing waves when a generator is matched to the line. Coupling to the generator, in A, figure 8, is usually made through a simple untuned transformer secondary. Another means of efficient energy transfer can be accomplished by a twisted-pair line (B, fig 8) that, like the coaxial cable, provides a good impedance match.

(2) When a line does not match the impedance of the antenna, special impedance matching devices must be used. The delta match (C, fig 8) is used to match a line, having more than 73 ohms of impedance, to the center of an antenna. The line in C, figure 8, is a 600-ohm line. The connections from the line are spread apart at the antenna until the impedance between the connections is 600 ohms. In the delta match, as the connections are moved away from center, the voltage increases and the current decreases. The ratio between the voltage and current increases from a very low value at the center to several thousand ohms at the end. The two-wire connections are set at the point where this E/I ratio is equal to 600 ohms. This is the same as matching various impedances along a shorted quarter-wave section of line.

(3) The quarter-wave stub (D, fig 8) is another method of matching impedance in which the high impedance at the end of the antenna matches the open end of the stub. The impedance of the stub varies from zero at the short circuit to several thousand ohms at the open end. This makes it possible to connect a 70-ohm coaxial line a short distance from the shorted end at the 70-ohm point. It is possible to match almost any impedance along the length of the stub.

(4) The quarter-wave transformer (E, fig 8) is still another impedance matching device that is used for matching the low impedance at the antenna to a line of higher impedance. Here, the characteristic impedance of the quarter-wave section should be 210 ohms for a proper match. Using this matching device, standing waves will exist on the antenna and the quarter-wave section, but not on the 600-ohm line.

(5) Nonresonant lines are characterized by small radiation losses, low voltage at all points for any given power, and noncritical length. In addition, they are preferred for the transfer of power over distances greater than one or two wavelengths.

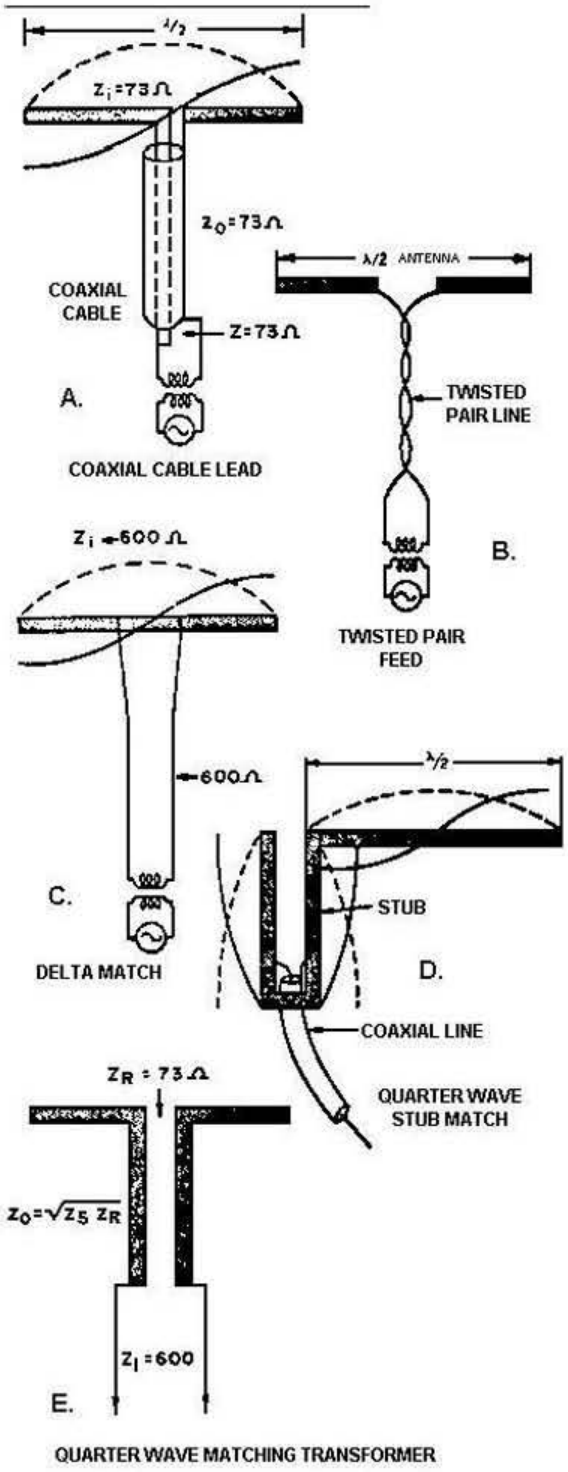


Figure 8. Feeding antennas with nonresonant lines.

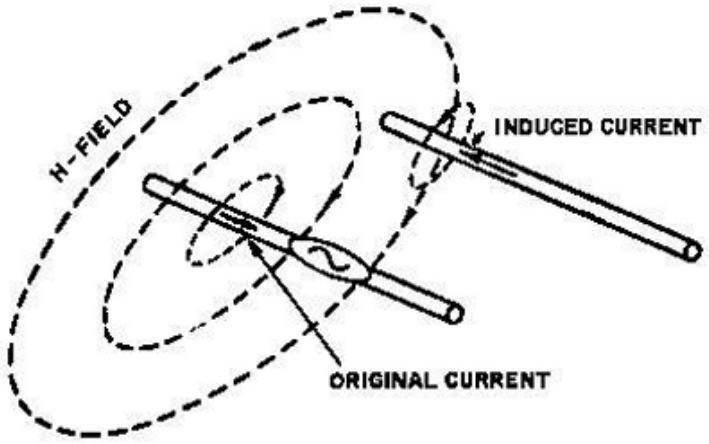


Figure 9. Exciting antenna by radiation field.

d. Exciting antennas by radiation fields.

(1) An antenna may be excited either by a direct connection or by radiation (induction fields) from nearby antennas. In figure 9, a half-wave antenna is driven by a directly connected generator. The flux from the driven antenna will expand and cut the other element, inducing a current. The induced current will vary at a frequency nearly equal to the excitation frequency and, in turn, will produce additional radiation fields. If the antenna elements are properly designed, the radiation fields resulting from the induced current will be almost as strong as the original radiation fields.

(2) An antenna may be excited by radiation fields from a distant transmitting antenna as well as by a nearby antenna. This is basically true of all receiving antennas where the current conducted to the receiver is the result of current induced by radiation fields generated by the transmitting antenna.

9. NONDIRECTIONAL ANTENNAS:

a. The half-wave antenna.

(1) Current and voltage distribution.

(a) As stated in paragraph 5, a half-wavelength conductor is the simplest of the radiating elements. Considerable radiation occurs in this element because of its resonant characteristics and its ability to store large amounts of energy in its induction fields. Resonance causes high voltages and high circulating currents, and they, in turn, produce strong fields around the antenna.

(b) In figure 10, the voltage standing wave is high at the ends of the antenna and low at the center. An examination of the current distribution curve shows that the current standing wave reaches maximum a quarter-cycle after the voltage. The current is maximum at the center and zero at the ends where there is no place for electrons to go. In practical applications, the ends of a half-wave antenna must be insulated due to the high voltages, and the center must have low resistances to minimize I^2R losses due to high current.

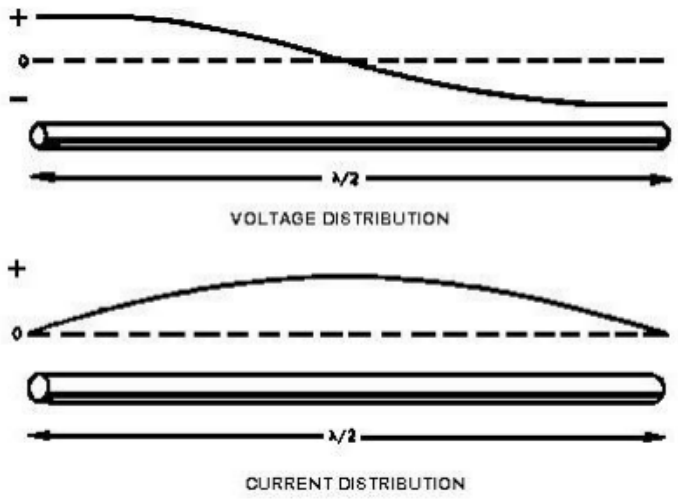


Figure 10. Current and voltage distribution of a half-wave dipole.

(2) Effect of length on antenna impedance. An antenna of the correct length acts like a resonant circuit and presents pure resistance to the excitation circuit. An antenna having some length other than that required for resonance will display both resistance and reactance. An antenna slightly longer than a half wave, for example, acts like an inductive circuit. Likewise, an antenna slightly shorter than half wave appears capacitive to the input.

(3) Input impedance of a dipole antenna.

(a) The input impedance of an antenna is the ratio of the voltage across the terminals (where the antenna is connected to the transmission line) to the current at the same point. If the antenna is resonant, the input impedance is restrictive. If there were no losses and no radiation, the value of this resistance would be zero. If there were energy losses, either through radiation or through copper and dielectric losses, the voltage and current at the input terminals would remain in-phase. Therefore, the input impedance would still be resistive. This resistance is a combination of two resistances: the resistance of the conductors themselves, which is increased by the skin effect at high frequencies, and the radiation resistance.

(b) Radiation resistance is a fictitious resistance that dissipates the same amount of power in the form of heat as it actually dissipated as radiated energy. Because of radiation resistance, an antenna allows part of its fields to escape into space. This necessitates additional antenna current to replace the part of the field that escaped. Therefore, the source must provide the energy lost by radiation. The energy lost is power (P) and its ratio to the square of the current (I) is the radiation resistance (R r). Mathematically it is expressed as $R_r = P/I^2$, and it is defined as the ratio of the power radiated to the square of the current in the antenna. It is possible to make the conductor resistance small in comparison to the radiated resistance by using large diameter, low resistance conductors. It is desirable that radiation resistance be the major portion of the input resistance. In practice, radiation ratios as high as 9:1 are obtainable and an antenna can be up to 90 percent efficient as a radiator.

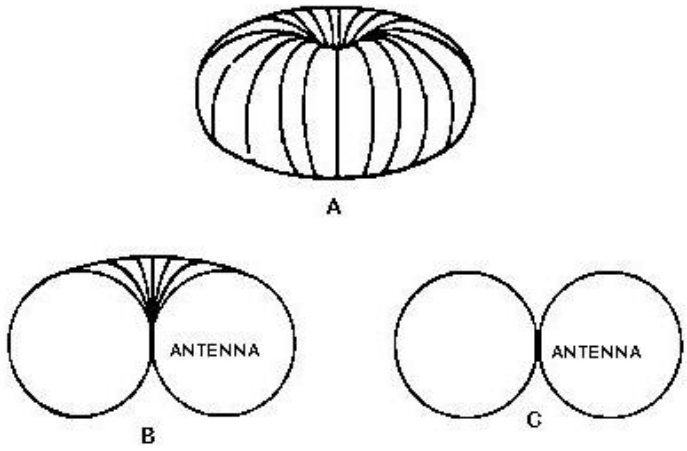


Figure 11. Radiation pattern of a dipole antenna.

(4) Radiation pattern of the half-wave dipole.

(a) Different antennas are compared by means of radiation patterns. We can explore the radiation field by using a length of wire orientated parallel to the antenna. Voltages induced in this wire are proportional to the field strength, which is measured in microvolts per meter. If the length of the wire is small, as compared to the wavelength, the voltage induced is proportional to the length of the wire. A standard field strength is arbitrarily chosen and all points in the field with this standard strength are connected. The result is the radiation pattern (fig 11A) for a dipole antenna, when it is located as shown in B.

(b) The radiation pattern may be shown by its projection in two planes. Since, for a dipole antenna, the projection in the plane perpendicular to the antenna is a circle, the section shown in C, figure 11, will usually be adequate to describe the pattern.

b. Marconi antenna.

(1) General. At a frequency of 1,000 KHz, which is the center of the broadcast band, a half-wave or Marconi-type antenna (fig 12) of this length can be cut in half. The distribution of voltage and current is similar to that in one-half of the half-wave antenna. This is true because of the capacitive coupling between the antenna and ground. When a capacitor is charged, the current flowing into one plate is equal to the current out of the other plate, even though the two plates are dissimilar. Since the transmission line is connected to the antenna at a point of high current, the current at the grounded point should be equally as large. Any resistance at this point of high current would cause a serious loss of power. For this reason, the ground should be a very good one. In order to obtain a low impedance to ground, a network of conductors extending symmetrically in all directions is sometimes buried in the earth.

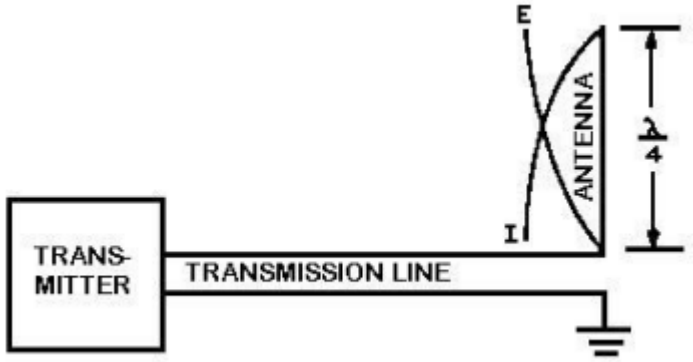


Figure 12. A Marconi antenna.

(2) Radiation pattern.

(a) The radiation pattern (fig 13) of a quarter-wave antenna is identical to one-half the radiation pattern of a similarly orientated half-wave antenna. This is true because ground reflections produce the same effect in any part of the pattern, as would a similar antenna positioned as shown in figure 14. If the earth is considered to be a perfect conductor, the reflection will be from a short circuit. That is, current is reflected in-phase and voltage out-of-phase. Therefore, the current thought of as flowing in the image antenna will be in the same direction as it would if the physical antenna with the image constituted a dipole antenna.

(b) With an antenna actually located close to the ground, where the reflections are strong, imagine an image antenna located a like distance below the surface of the earth with its current in phase with that of the actual antenna. The resultant radiation pattern will appear as if both antennas are present, and the radiation resistance will be one-half that of a normal dipole.

(3) Antenna loading. Because of the expense of building a tower high enough for a quarter wave at the lower broadcast frequencies, antennas are often loaded with inductance to increase their effective length. An antenna of less than a quarter wave will present a capacitive load to the transmission line. The proper addition of inductance (A, fig 15) will cancel out the reactive component of the load and resonate the antenna. It is also possible to resonate an antenna longer than a quarter wave by adding an amount of capacitance (B, fig 15). Parallel inductance and capacitance are also used for tuning an antenna (C, fig 15).

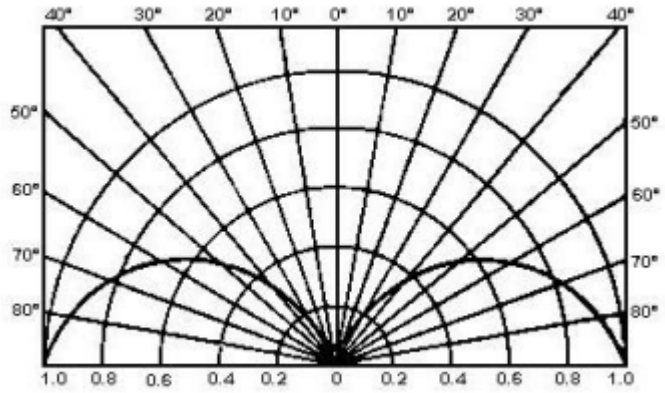


Figure 13. The radiation pattern of a Marconi antenna.

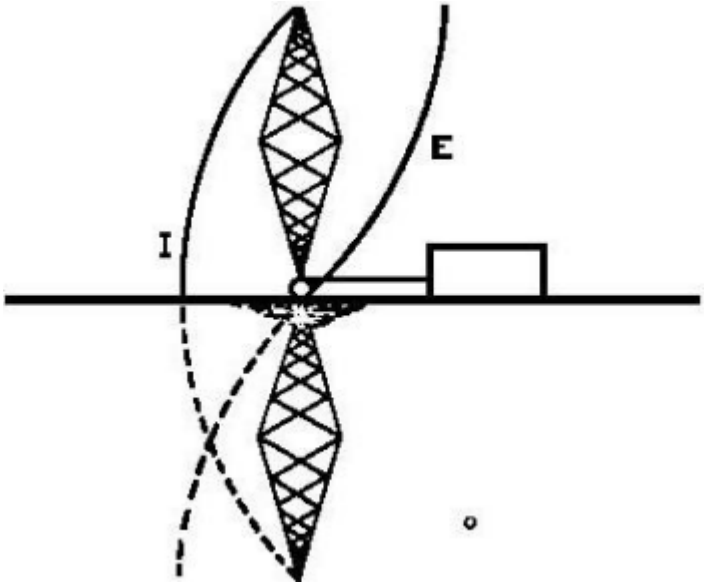


Figure 14. The image antenna.

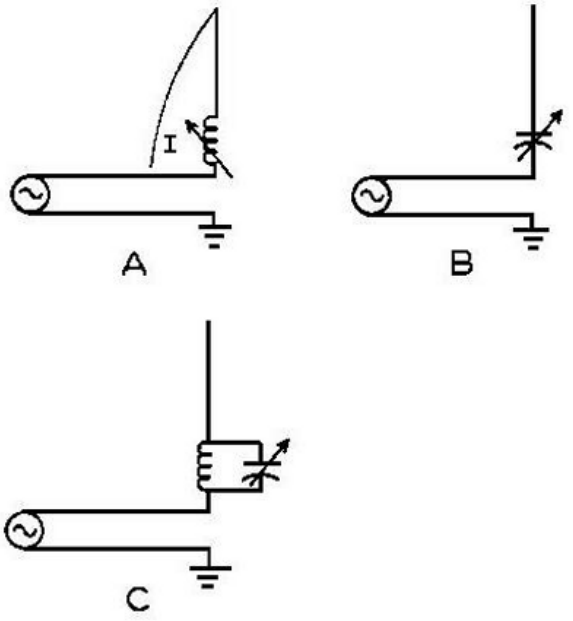


Figure 15. Loading of broadcast antennas.

(4) Effect of antenna length. An antenna is often made longer than its resonant length in order to improve the radiation pattern. Figure 16 shows the radiation patterns of antennas of different electrical lengths. Although the pattern that achieves the flattest distribution of radiated energy is about 5/8 of a wavelength, it is seldom economical to build such an antenna for the sake of the improved radiation pattern. Rather, there must be a compromise between the cost of the antenna, the cost of the transmitting station, and the operating costs if the widest possible coverage for the least cost is to be obtained.

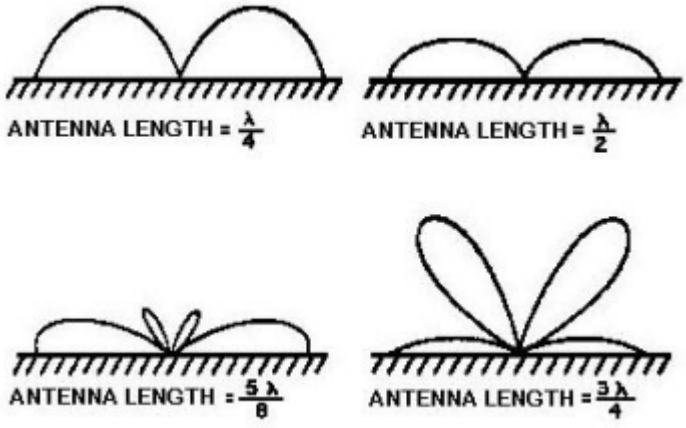


Figure 16. The effect of antenna length on the radiation pattern.

10. POLARIZATION OF AN ELECTROMAGNETIC WAVE.

a. An electromagnetic field in space is said to be polarized, and the direction of the electric field (E-lines) is considered the direction of polarization. As the electric field is parallel to the axis of the half-wave dipole, the antenna is in the plane of polarization. Therefore, when the half-wave dipole is horizontally orientated, the emitted wave is horizontally polarized (fig 17). Likewise, a vertically polarized wave is emitted when the antenna is vertically erected.

b. For maximum absorption of energy from the electromagnetic fields, a half-wave dipole should be located in the plane of polarization. This places the conductor at right angles to the magnetic lines of force and parallel to the electric lines.

c. Generally, the polarization of a wave does not change over short distances, but may shift somewhat over longer distances. Therefore, transmitting and receiving antennas are usually orientated alike, especially if only short distances separate them. If the separation is of some magnitude, then polarization will change quite rapidly, especially at the higher frequencies.

d. With radar transmission, a received signal is a wave reflected from some object. Since the polarization of the reflected signal varies with the type of object, no set position of the receiving antenna is correct for all returning signals. Generally, the receiving antenna is polarized in the same direction as the transmitting antenna.

11. DIRECTIONAL ANTENNAS.

a. General.

(1) Some uses for antennas require that the radiation be absolutely nondirectional, while others require that the antenna be sharply directional. Even in a commercial broadcast it is sometimes not desirable to broadcast a circular pattern. If the station were located on a beach, there would be no need to radiate energy over the water. Another reason for wanting to limit the radiation to one direction might be the possibility of interference with another broadcasting station on or near the same frequency.

(2) An antenna system that is directional, or limited, may consist of two or more simple half-wave elements so spaced that their fields add in some directions and cancel in others. Such a set of elements is called an antenna array. There are two types of antenna arrays–driven and parasitic. We will first discuss the driven arrays; i.e., endfire, broadside, and collinear.

b. Driven arrays.

(1) The endfire array.

(a) In figure 18A, two dipole antennas separated by a half-wavelength are excited at the same frequency. Figure 18B, shows the H-field being radiated from antenna 1 at a certain instant. Notice that the lines are a half-wavelength apart and that they show the direction of the H-field at current maximums. At points a half-wavelength apart, such as P and M, the direction of the H-lines is opposite. Figure 18C shows the H-field that results from separate excitation of antenna 2. A comparison of point N (fig 18C) with point M (fig 18B) shows that the H-lines, a half wave from the antennas, are in opposite directions. Therefore, the antennas must be excited in opposite phase.

(b) Figure 18D shows the separate H-fields which result from simultaneous, opposite phase, excitation of the two antennas. The H-lines (B and C, fig 18) are superimposed to determine the nature of the resultant field. Solid and dotted lines intersect at points E, F, G, and H (fig 18D). At points G and H, the arrows on the two lines have the same direction. It can, therefore, be concluded that a strong field exists in the directions OH and OG. At points E and F, however, the arrows on the solid lines are in opposite directions to those on the dotted lines. Thus, the resultant field in the directions OE and OF is very weak.

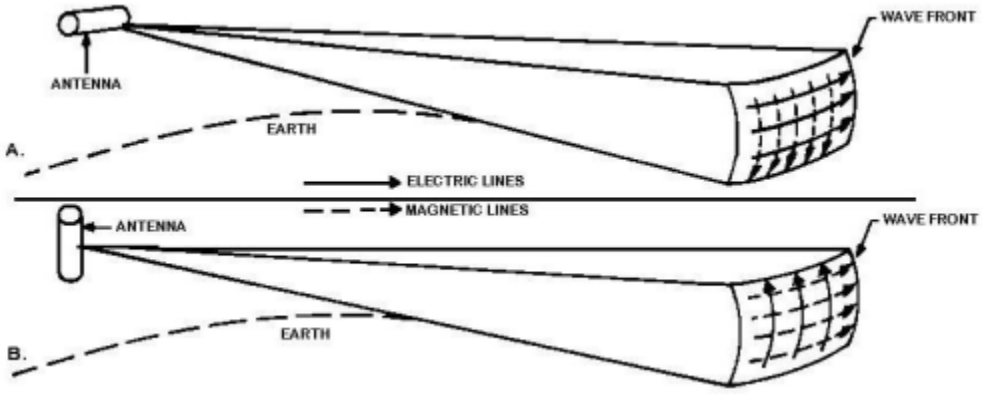


Figure 17. Horizontal and vertical polarization.

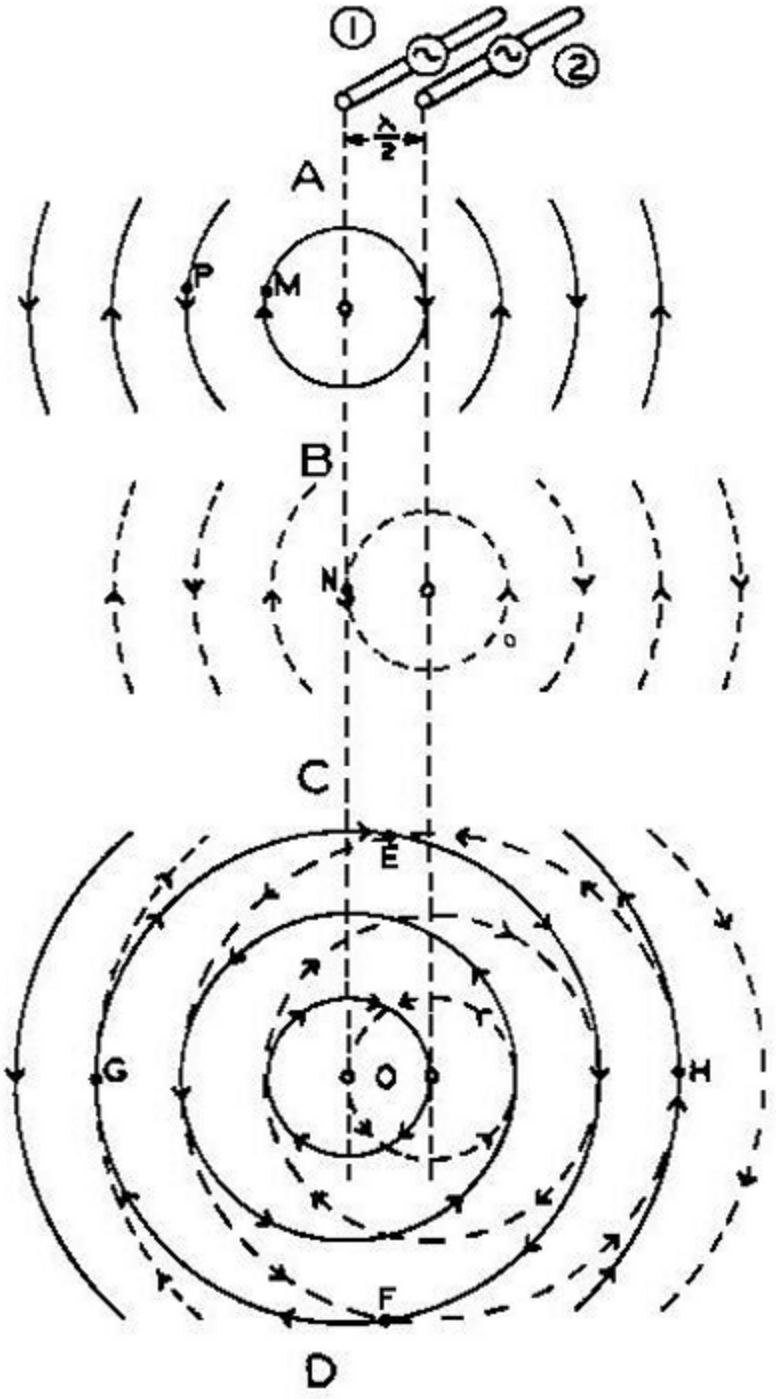


Figure 18. Individual H-fields of two dipoles in an endfire array.

(c) Two dipoles, spaced a half wavelength apart and fed out-of-phase, is one of the basic arrays and is called an endfire array. There are several variations of the endfire array. For instance, its directivity may be increased by adding additional dipoles with the same spacing and phasing. Figure 19A shows such an array consisting of eight dipoles. The adjacent dipoles are fed out-of-phase by the simple method of connecting them to points a half wavelength apart on a transmission line. The voltage at Point A, figure 19A, is 180 degrees from that at point B because these points are a half-wavelength apart.

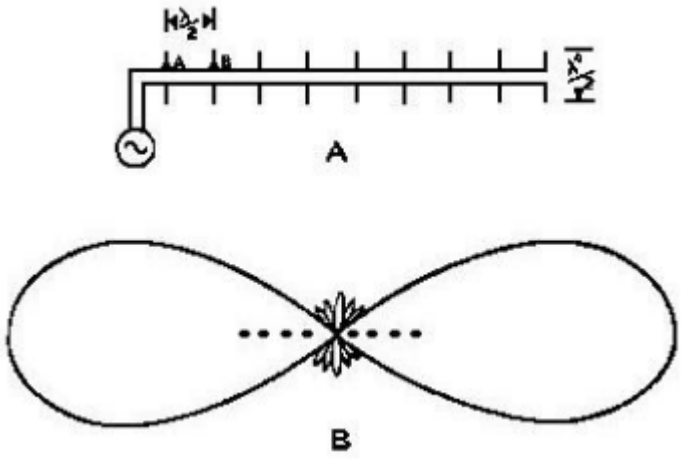


Figure 19. (A) An endfire array. (B) Radiation pattern of an endfire array.

(d) Figure 19B shows an end view of the same antenna elements with the radiation pattern. Since the pattern has two lobes, it is called a bi-directional antenna. The spacing and phasing of the dipoles may be changed to produce a one lobe or unidirectional pattern. Such an array is still described as endfire, as long as the direction of its maximum radiation is from the ends of the array. On the other hand, if the direction of maximum radiation were perpendicular to the dipoles and to their common plane, it would be known as a broadside array.

(2) The broadside array.

(a) The array in figure 19A could be converted to a broadside array by feeding the dipoles in-phase. In figure 18D, if the arrows on the dotted lines were reversed, the fields would be in-phase. Cancellation would then occur at points G and H (fig 18D) and reinforcement at E and F. Maximum radiation would be in directions OE and OF and minimum radiation in OG and OH.

(b) Figure 20A shows how the array is connected to bring the dipoles in-phase. Points A and B are in opposite phase because they are on the same conductor of the transmission line and separated by a distance of a half-wavelength. Points B and C are also in opposite phase because they are at opposite points on the transmission line. Since points A and C are both 180 degrees out of phase with point B, they must be in phase with each other. The basic broadside array, then, consists of dipoles spaced a half-wavelength apart and fed in-phase.

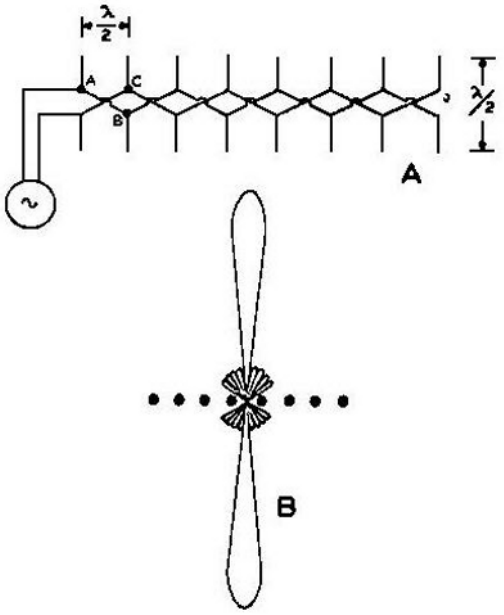


Figure 20. (A) A broadside array. (B) Radiation pattern of a broadside array.

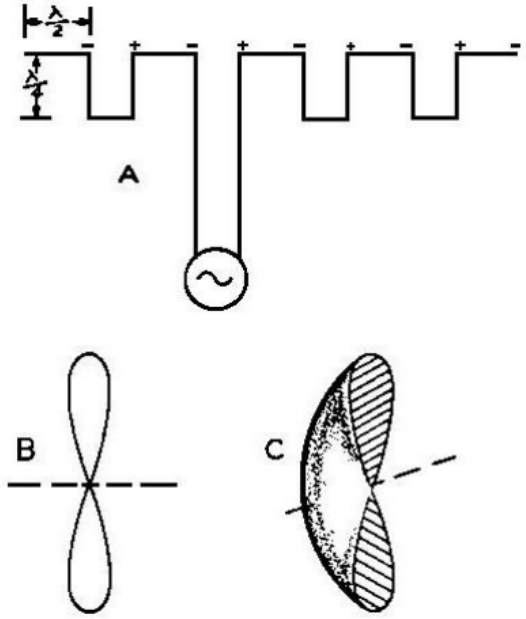


Figure 21. (A) A collinear array. (B) A radiation pattern for the collinear array.

(c) Figure 20B shows that the broadside array is a bi-directional antenna. The lobes are longer and more narrow than those of the endfire array (fig 19B). Therefore, the broadside array is considered to be more directional than the endfire array.

(3) The collinear array.

(a) A collinear array consists of a series of dipoles placed end to end and fed in-phase. They may be phased by using quarter-wave-shorted stubs as shown in figure 21A. Since these stubs are resonant, there will be high voltage points where the plus and minus signs are indicated. The plus sign does not indicate that the point so marked is always positive, since the polarity of all points changes every half-cycle.

(b) Figure 21B shows the outline of the radiation pattern with reference to the line of the array. Figure 21C shows that this pattern is actually circular in the perpendicular plane, and that a half pattern of radiation from a collinear array is similar to that of a dipole (fig 11). The essential difference is that the array pattern is thinner. If the dipole pattern is thought of as a doughnut, the collinear array pattern would be a stepped on, flattened doughnut--and the more dipole elements in the array, the flatter the doughnut becomes.

c. Parasitic antenna arrays.

(1) A parasitic array is an antenna system that consists of two or more elements in which only one of the elements is driven. The other element (or elements) is excited by induction and radiation fields produced by the driven element. It is possible to obtain highly directional patterns using parasitic arrays.

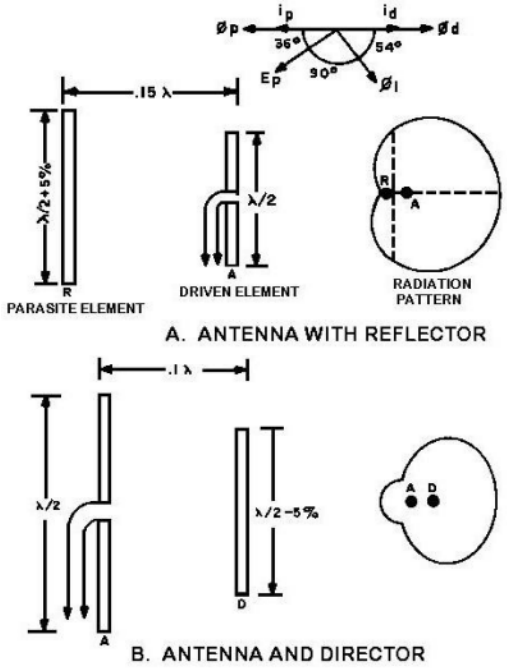


Figure 22. Two-element parasitic arrays.

(2) The action of a parasitic array can be compared to the action of a transformer; i.e., the primary induces a current in the secondary that, in turn, produces a magnetic field. The magnetic field, however, will induce current back into the primary. The parasitic action differs from that of a transformer in that the phase relationship between array elements varies according to their spacing, while the transformer primary voltage and secondary currents is always 90 degrees out-of-phase. The parasitic elements are usually spaced so that the phase difference can be varied over a range of more than 80 degrees.

(3) A two-element array (fig 22A) has the driven element cut at the center for connecting a low impedance feedline. The length of the driven element is a half-wavelength and is self-resonant. The parasitic element is 15 percent of a wavelength from the driven element and is 5 percent longer.

(4) The radiation pattern for two elements spaced 0.15λ apart and excited out-of-phase is shown in figure 22A. Note that most of the radiated energy is on the side of the driven element and that only a small amount is on the side of the parasite. Because it acts somewhat like a reflector (it causes most of the power to be radiated toward the side of the driven element), this type of parasite is called a reflector.

(5) A parasitic element becomes a director when it is cut shorter than the antenna element. In a director, most of the energy is directed from the antenna element toward the parasitic element. Note the radiation pattern and arrangement of the two-element array in figure 22B. The director is usually 5 percent shorter and is spaced about 0.1λ from the antenna.

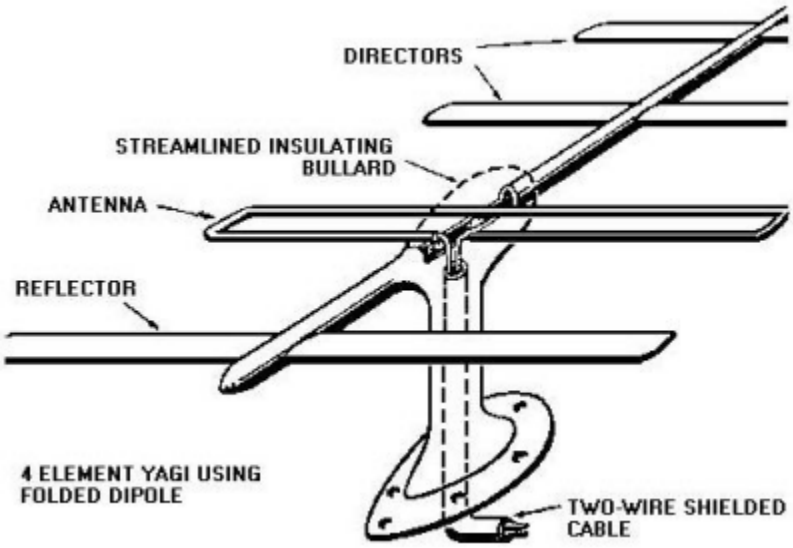


Figure 23. Yagi array.

(6) In radar systems, the parasitic array will usually consist of from 2 to 7 elements. Notice the 4-element Yagi array in figure 23, where the antenna, or driven element, is insulated and the reflectors and directors are welded to a piece of tubing that runs parallel to the direction of propagation. This array has a beam width of approximately 50 degrees.

(7) The directivity of an array is expressed in terms of the ratio of power in the best lobe to either the power radiated by a simple half-wave antenna or the power in the opposite direction. The direction of the best lobe is usually called the forward direction, while that in the opposite direction is called the backward direction. In other words, directivity is the ratio of power in the forward field to that in the backward field. For example, the front-to-back ratio of the antenna in figure 23 is approximately 5:1.

(8) Comparisons between the more directive types of arrays are made in terms of the beam angle; i.e., the angle between half-power points in the main lobe. The width of the beam is the angle included between the lines drawn from each of two half-power points to the transmitting antenna (fig 24). A circular arc is drawn using the transmitting antenna as a center and any convenient radius. Field strength readings are taken at several points along this arc. For example, point A is the point of maximum field strength as indicated by a voltage reading. Points B and C have voltage readings which are 0.707 times the reading at A. The angle theta (θ) is the beam width and may be different in the vertical and horizontal planes.

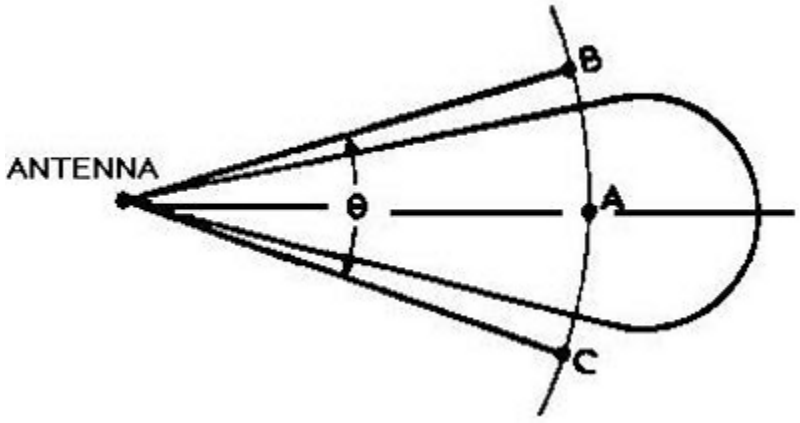


Figure24. The beam width is determined by the half-power points.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 7

1. What BEST describes antenna reciprocity?

   A. Capability of one antenna to both code and decode

   B. Ability to radiate and receive from all directions

   C. Ability to monitor any transmitted frequency

   D. Capability of one antenna to both transmit and receive

2. What characteristic, if increased, serves to improve antenna efficiency?

   A. Beam width

   B. Line circuit impedance

   C. Beam directivity

   D. Tank circuit impedance

3. Why does the quarter-wave (Marconi) antenna behave as a dipole?

   A. Because it is center fed

   B. A quarter-wavelength of conductor is buried in the ground and forms the rest of the dipole

   C. An image antenna is formed by reflections from the ground

   D. The applied signal is rectified so that only half the signal will appear on the quarter-wave antenna

4. What BEST describes the radiation field intensity of an antenna?

   A. Increases as the distance increases

   B. Decreases with the square of the distance from the antenna

   C. Decreases linearly as the distance increases

   D. Increases with the square of the distance from the antenna

5. A driven element

   A. derives its power from another element.

   B. is always a quarter-wave dipole.

   C. is parasitic.

   D. is connected directly to the transmission line.

6. At what point is energy introduced to a voltage-fed antenna?

   A. Minimum tank voltage

   B. Maximum voltage

   C. Maximum current

   D. Minimum voltage

7. What is an advantage of feeding antennas with resonant lines?

   A. Makes coupling devices unnecessary

   B. Makes matching devices unnecessary

   C. Increases production of radiation fields

   D. Increases production of standing waves of current

8. What is the purpose of a delta match?

   A. To match a coupling between the receiver and transmitter circuits

   B. To match a line and antenna that have equal impedances

   C. To match a coupling between the receiver and modulator circuits

   D. To match a line and antenna that have different impedances

9. What is the input impedance of a resonant antenna?

   A. Inductive

   B. Capacitive and inductive

   C. Resistive

   D. Resistive and reactive

10. What is an advantage of the Marconi antenna?

   A. A shorter physical length

   B. The radiation resistance is the same as a normal dipole for identical frequencies

   C. The radiation pattern is identical to that of a similarly orientated half-wave antenna

   D. A higher frequency application

11. What determines the direction of electromagnetic field polarization?

   A. H-field

   B. E-field

   C. Length of the antenna

   D. Emission pattern of the antenna

12. How should a half-wave dipole antenna be oriented for maximum energy absorption?

   A. Perpendicular to the plane of polarization

   B. Parallel to the magnetic lines of force

   C. Perpendicular to the electric lines of force

   D. Parallel to the plane of polarization

13. What is the element configuration of a two-dipole, endfire array antenna?

    A. A half wavelength apart and fed in-phase

    B. A half wavelength apart and fed out-of-phase

    C. One wavelength apart and fed in-phase

    D. One wavelength apart and fed out-of-phase

14. What BEST describes the radiation pattern of the endfire array antenna?

    A. Unidirectional

    B. Omnidirectional

    C. Bi-directional

    D. Unidirectional and perpendicular to the dipoles

15. Which is the MOST directional antenna?

    A. Marconi

    B. Endfire array

    C. Broadside array

    D. Half-wave dipole

16. The radiation pattern of the collinear array can be flattened by

    A. adding dipole elements.

    B. feeding dipoles in-phase.

    C. deleting dipole elements.

    D. feeding dipoles out-of-phase.

17. How many elements are driven in a parasitic array antenna?

A. One

B. Two

C. Three

D. Four

18. What modification allows a parasitic array to be employed as a reflector?

A. Cutting the element shorter than the driven element

B. Cutting the element longer than the driven element

C. Adding additional parasitic elements of the same length

D. Adding additional reflector elements of the same length

19. The broadside array is what type antenna?

A. Parasitic

B. Nondirectional

C. Omnidirectional

D. Driven

20. Comparisons between directive array antennas are made on the basis of what factor?

A. Beam angle

B. Polarization of received energy

C. Polarization of radiated energy

D. Beam direction

LESSON 8. HIGH FREQUENCY OSCILLATORS AND PULSE MODULATORS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, function, and use of high frequency oscillators and pulse modulators.**
Lesson Credit Hours.....	**Three**

TEXT

1. GENERAL.

a. The generation and amplification of ultra high frequency (UHF) and super high frequency (SHF) signals are a major problem encountered in the field of radar. The term microwave includes the UHF and SHF bands, and it will also include those of higher frequencies if and when they are developed. Conventional oscillators are very inefficient, even at the lowest carrier frequencies (100 MHz), and there are several basic reasons for this inefficiency.

(1) In our study of vacuum tubes we learned that the elements of a tube form small capacitors (a capacitor is any two conductors separated by a nonconductor). This capacitance is called interelectrode capacitance and at audio or low radiofrequencies does not interfere with tube amplification. However, when we use the same tube for ultra high frequencies the capacitance reactance, offered by the interelectrode capacitance, goes down ($X_c = \frac{1}{2} \pi f c$). If X_c becomes low enough, the tube will simply act as a short circuit to the UHF and the signal will pass through the tube without being amplified.

(2) Another frequency limiting factor of a conventional oscillator is the lead inductance of each element. These inductances, which have a negligible reactance at low radiofrequencies, begin to have considerable reactance at higher frequencies. Since the inductance of the cathode lead is common to both grid and plate circuits (fig 1), its reactance causes a degenerative feedback that reduces the amplitude of oscillations at the higher frequencies.

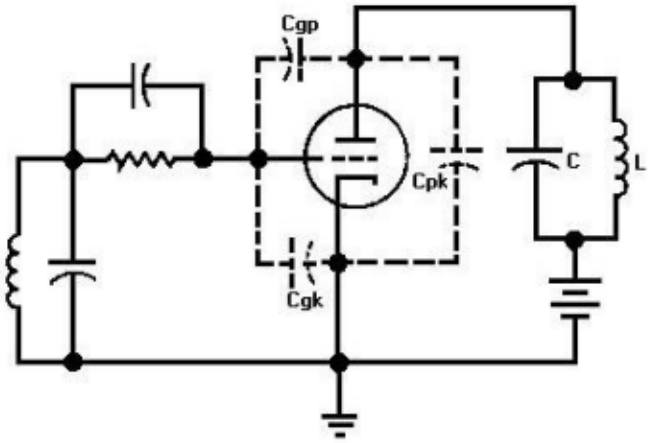


Figure 1. A TPTG oscillator with interelectrode capacitance.

(3) The physical construction of a tube also limits the frequency that may be generated by a conventional oscillator. Transit time is the time required for electrons to travel from the cathode to the plate of a tube. In low-frequency operation, this time is disregarded because it is negligible when compared with the time for one cycle. Thus, the grid voltage and plate current are considered to be in phase and the plate voltage to be 180 degrees out of phase with them. At higher frequencies, however, this transit time becomes appreciable when compared to one wavelength. It has been found experimentally that at frequencies where transit time is greater than one-tenth of a cycle, the efficiency of the conventional oscillator drops considerably. Finally, when transit time approaches a quarter of a cycle, the oscillator cuts off.

(4) Dielectric losses between the tube base and the envelope are also construction losses, which are objectionable at high frequencies. These losses greatly reduce the output and efficiency of conventional oscillators when used at these frequencies.

(5) As the frequency increases, conventional oscillators also have limitations due to the external circuits of the oscillator. Because current flows in a thin layer on the conductor's surface, an increase in frequency will cause a considerable resistance increase in a vacuum tube circuit. As the frequency increases, the depth of the layer becomes thinner and the I^2R losses due to the "skin effect" become greater.

(6) Radiation loss is caused by an incomplete cancellation of electromagnetic fields in the region surrounding the circuit. At low frequencies a spacing between conductors, which represents only a small fraction of a half-wavelength, causes complete field cancellation. At the frequency where the spacing represents a half-wavelength, the fields will add in the conductors' plane causing radiation as though from an antenna.

b. The limitations due to physical structure may be overcome by constructing tubes of special types. Low interelectrode capacitance may be attained by means of small, widely spaced electrodes. Although the reduction of interelectrode capacitance is made possible by an increase in the spacing between electrodes, it also has the adverse effect of increasing transit time. Hence, UHF tubes tend to have small electrodes which cause them to have low power capabilities.

c. Reducing the physical size of the tube and making the leads shorter and of larger diameter can reduce the lead inductances. The leads in most UHF tubes are brought out through the tube envelope and do not use a conventional tube base. Dielectric losses can also be reduced by projecting the leads through the glass envelope at voltage node points.

d. Transit time may be reduced by closer electrode spacing and higher plate voltages. Since bringing the electrodes closer together increases the tube interelectrode capacitance, this method is used only if the electrodes are made smaller at the same time. In most cases, however, transit time is reduced by applying higher plate voltages.

2. ULTRA HIGH FREQUENCY TUBES.

a. Acorn tubes. Two acorn tubes, one a triode and the other a pentode, are shown in figure 2. Called acorn tubes because of their appearance and small size, the internal arrangement of these tubes is similar to that of a conventional tube. They have small spacing between the electrodes to reduce transit time, small electrodes to reduce interelectrode capacitance, and short, thick leads to reduce lead inductance. Note that the leads are brought directly through the glass with no conventional tube base used. These tubes are designed for efficient operation as oscillators or amplifiers at frequencies up to approximately 300 MHz. However, frequencies up to 600 MHz may be obtained, but efficiency will be very low.

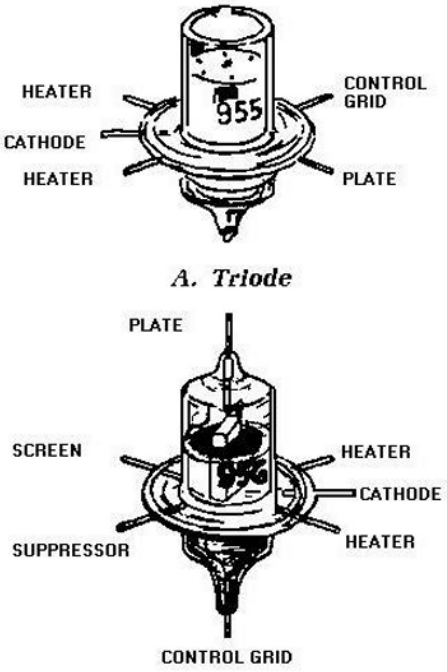


Figure 2. Acorn tubes.

b. The lighthouse tube.

(1) The lighthouse tube (fig 3), so called because of its shape, is another single-tube oscillator designed to operate in the UHF range. Although it can efficiently operate at frequencies up to 3,600 MHz, its output peak power is somewhat limited. Designed especially for use with concentric line tuners, its major advantage is that the tube capacitance can be made part of the resonant circuits and, since all RF components are located inside a coaxial cable, there is no radiation loss. Therefore, this tube is normally used in a fairly low-power capacity and either as an oscillator, converter, or transmitter.

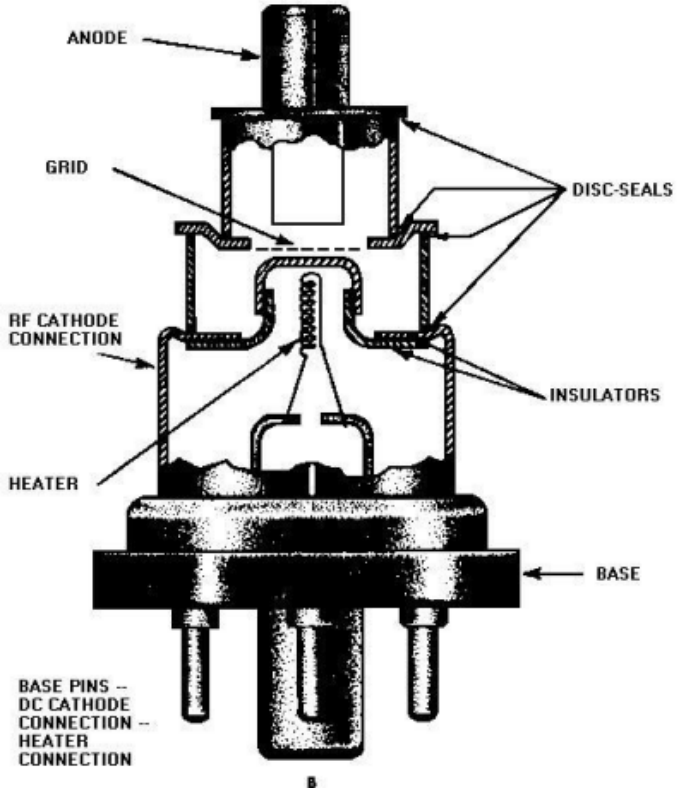


Figure 3. A typical lighthouse tube.

(2) The lighthouse tube is called a disk-seal tube because the electrode connections are brought out through disks which are sealed into the glass envelope. It is usually mounted within a tuning assembly composed of three cylindrical coaxial conductors (fig 4). The inner conductor makes contact with the plate, the next conductor with the grid, and the outer one with the shell of the tube, which is connected to the cathode both externally and through interelectrode capacitance. The space between the cathode and grid conductors forms a coaxial cathode line short-circuited by an adjustable plunger. Although the plunger does not actually touch the grid conductor, the capacitance between the two provides an RF short circuit. The DC grid to-cathode path, consisting of R g and C g (fig 4), forms the grid leak bias network.

(3) The plate line, which is open-circuited at the end away from the tube, is formed by the grid and plate conductors. Voltage is applied to the plate through the plate-tuning rod at a point where the plate line is short-circuited. The quarter-waveline section behind this short acts as an RF choke, presenting a high impedance and keeping RF out of the power supply.

(4) Since the shorted cathode line is slightly less than ¾ of a wavelength, it acts like an amount of inductance. The open-circuited plate line, slightly less than one wavelength, also acts like an amount of inductance. Although these dimensions are chosen for a frequency of approximately 3,000 MHz, the shorted cathode line will act just as effectively as an inductance if it is slightly less than a quarter-wavelength or any odd multiple of a quarter-wavelength, at any frequency. The open-circuited plate line will also effectively act as an amount of inductance if it is slightly less than a half-wavelength.

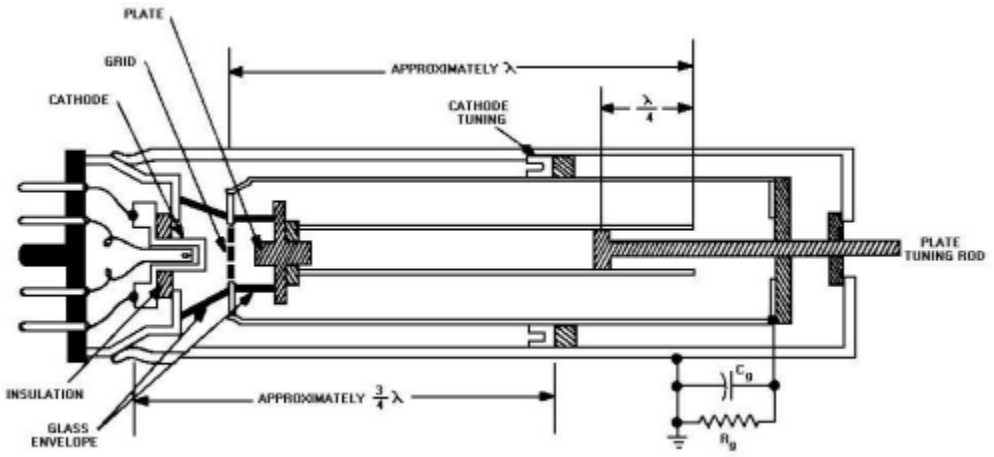


Figure 4. A lighthouse tube and tuning assembly.

(5) For oscillations to occur in a lighthouse tube, the plate line must be tuned inductively and the cathode line must be tuned capacitively. Thus, the plate circuit must be tuned to a higher frequency than the cathode circuit, and the oscillations which occur are at a frequency somewhat between the two. The tuning of the cathode line principally controls the oscillation frequency; therefore, because of the interaction between these tuning controls, it is often necessary to readjust each line to obtain maximum output at the desired frequency.

c. Reflex klystron.

(1) General.

(a) In radar most receivers use 30 or 60 megahertzs intermediate frequencies. In superheterodyne receiver operation the frequency stability of the local oscillator is a highly important factor. For example, in a radar receiver that receives a frequency of 3,000 MHz, a local oscillator frequency shift of 0.1 percent is a 3-MHz frequency shift. This is equal to the bandwidth of most receivers and would cause a considerable signal loss in the receiver.

(b) A radar local oscillator must also be easily tunable, over a range of several megahertzs, to compensate for changes in the transmitter frequency and in its own frequency. In cases where the RF units are located in a remote position, the receiver converter section may be mounted near the transmitter. Thus, the intermediate frequency (IF), rather than the transmitted frequency, is cabled back to the receiver. Therefore, it is often necessary that the local oscillator be tunable by a variable voltage applied from a distant position.

(2) Circuit operation.

(a) A reflex klystron is a tube that uses a resonant cavity as a tank circuit and generates microwave frequencies. It is known as a velocity-modulated tube because the various electrons it emits are accelerated or decelerated at different rates (thus varying their velocities).

(b) Figure 5 illustrates the arrangement of electrodes and the voltages involved in the operation of a reflex klystron. Electrons are emitted by an indirectly heated cathode. These emitted electrons are then attracted by the control grid and cavity grids (all positive in respect to the cathode). The control grid, located between the cathode and cavity grids, controls the flow of electrons from the cathode and focuses them into a beam. Most of the emitted electrons, traveling at a high velocity, pass through the control grid, the cavity grids, and continue on toward the repeller plate. Since the repeller plate is about 130 to 190 volts negative, with respect to the cathode, the electrons come to a region (after passing the cavity grids) where the electrical field opposes their motion. This opposing negative voltage slows down the electrons causing them to come to a stop, reverse direction, and return through the cavity grids. They are then collected either by the control grid, the shell, or the cathode of the tube. Obviously, the distinguishing feature of this tube is the repeller plate or the reflector, which gives the reflex klystron its name.

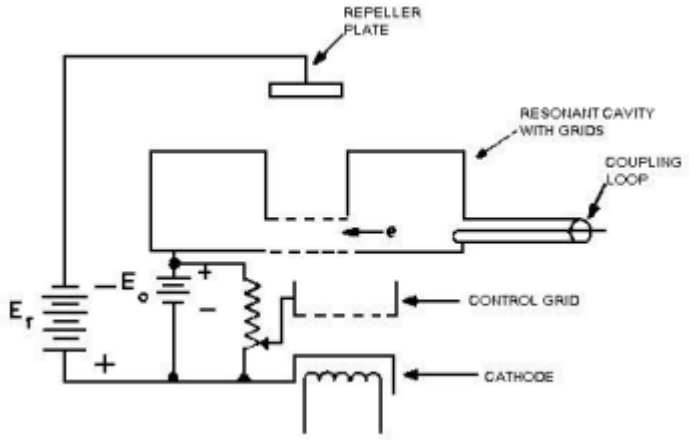


Figure 5. Reflex klystron circuit.

(3) Oscillatory action.

(a) In most oscillators, oscillations start from some irregularity in current flow, such as a transient which results from sudden voltage application to the tube. With this in mind, assume that oscillations in the resonant cavity are already taking place and, from this assumption, examine the source of the energy needed to sustain these oscillations. With the circuit oscillating, a high frequency voltage (e) appears between the two cavity grids. This makes the electric field between these grids reverse twice during each cycle of operation.

(b) As the electrons approach the cavity grids, the electron stream is fairly uniform. The time required for the electrons to pass through the small separation between the grids is short, as compared to the total period (time) of one oscillation. Electrons entering the space between the grids, when e is zero, do not encounter an AC electrical field and pass on at the same velocity. The electrons entering the space when e has made the bottom grid (fig 5) positive, with respect to the top, will encounter a field that tends to accelerate them. Likewise, electrons entering the space when e is reversed in polarity are decelerated. The amount of acceleration and deceleration depends upon the magnitude of e. The change in velocity due to acceleration and deceleration is small, as compared to the original velocity. The electrons experiencing the greatest acceleration will travel further toward the repeller plate before being turned back; while those decelerated most will be turned back quickest. As a result of these different amounts of applied force, the electrons return to the cavity grids in bunches (fig 6).

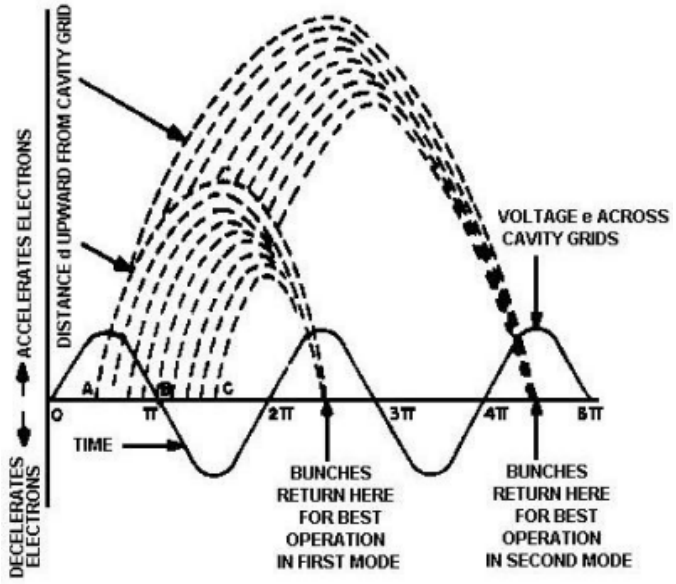


Figure 6. Bunching action of reflex klystron.

(c) Figure 6 shows the position of the electrons at various times during their transit. Note that the zero distance position is midway between the cavity grids. Electron A, which arrives when e is positive, is accelerated and travels further toward the repeller plate before being turned back. Electron B is unaffected, but electron C is decelerated and turned back after traveling a short distance. In figure 6, these electrons, and the ones passing through at intermediate times, are shown arriving back at the grids at the same instant. This is the ideal situation.

(4) Sustaining oscillations.

(a) On the return trip the electric fields set up by the voltage (e) again act upon the electrons. Since they are now traveling in the opposite direction, they will be decelerated if they return when e is positive, and accelerated if they arrive when e is negative.

(b) When an electric field accelerates an electron, it also increases the kinetic energy of the electron by taking energy from its own field. On the other hand, a decelerated electron gives up energy to the electric field. Therefore, for maximum energy transfer to the alternating field, the bunches of electrons must arrive back at the grid when e is maximum positive.

(c) If the electron stream from the cathode is uniform, some electrons will be accelerated and others decelerated on the outbound trip by the electric field of e. On the average, as many electrons will absorb energy from the field as give up energy to it; hence, very little net energy is taken from the oscillating circuit during the bunching process. Rather, the average kinetic energy of the electron is that amount imparted to it by the DC voltage, and the oscillations are sustained by transferring energy from the DC field to the AC field.

(5) Modes of operation.

(a) Referring to figure 6, it is noticeable that the bunches of electrons do not necessarily return to the grids exactly on the first positive swing of e. For example, the transit time for electron B may be ¾ cycle, 1-¾ cycles, 2-¾ cycles, etc. In actual practice there are several modes in which the velocity-modulated tube can oscillate. The solid lines indicate paths of electrons operating in the first mode, while the dotted lines indicate paths of electrons operating in the second mode. A third mode is also possible when the average transit time is 2-¾ cycles.

(b) The different modes (points of oscillatory action) are created by controlling the transit time of the electrons. Since the original electron velocity depends on the DC voltage (E a) (fig 5), the distance that the electron travels before being turned back and the speed with which it returns are controlled by the difference between E a and E r. Thus, the two voltages E a and E r can be adjusted to operate in any of the modes. Although E a is usually a fixed value, E r is normally variable and used to select the desired mode. For example, to operate in the first mode (fig 6), the repeller plate is made maximum negative and the electron round trip is completed in the shortest time. Thus, the other modes are achieved only by decreasing E r as necessary.

(c) Figure 7 illustrates the power output and frequency of oscillations as functions of the repeller voltage for three modes of operation. Notice that the frequency at the point of maximum output is the same for all three modes (resonant frequency). In addition, note that the output power for the various modes is not the same at resonance. In fact, the highest mode has the smallest output. The band of frequencies obtained by varying the repeller voltage lies between the half-power points of the mode. Thus, the range of usable frequencies is known as the electrical bandwidth.

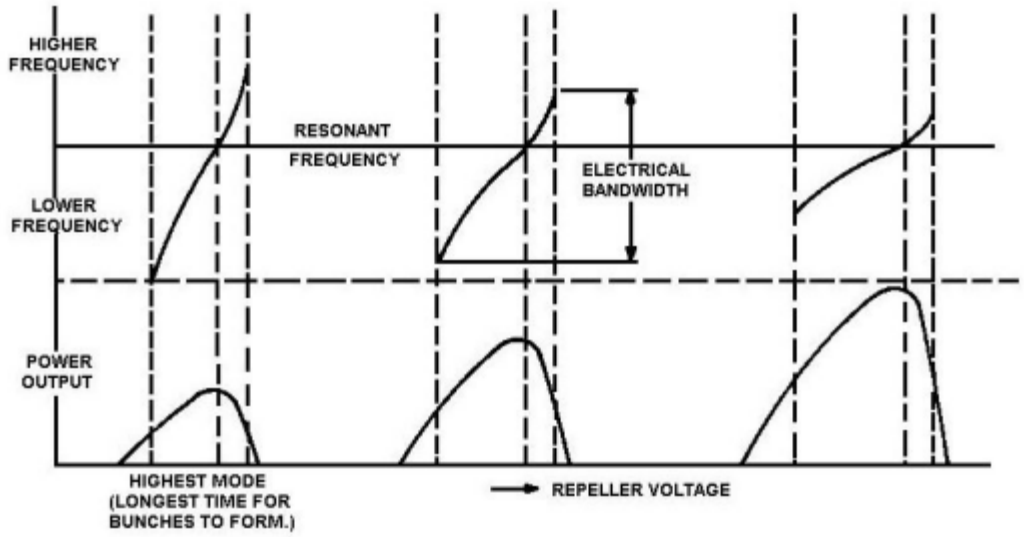


Figure 7. Power output and frequency versus repeller voltage.

(d) The choice of the point and mode of operation is a compromise among several factors. To begin with, there are three or four modes which have the necessary output power. It would seem that the correct choice would be the highest mode since it gives the widest tuning range; however, the highest mode is too sensitive to changes in voltage to be well regulated. For example, a change of only one volt may cause a 0.5 MHz change in the 3,000 MHz oscillator. Also, since the humps (fig 7) are unsymmetrical, the chosen point of operation is usually a little below the point of maximum output. This makes it possible to tune above and below the operating point by approximately an equal amount.

(6) Circuit application.

(a) In practice, the reflex klystron is usually used in conjunction with an automatic frequency control (AFC) circuit that maintains the correct intermediate frequency by controlling the repeller voltage. Although the oscillation frequency is primarily determined by the cavity dimensions, the repeller voltage is effective for small frequency changes. In most reflex, velocity-modulated tubes, the coarse frequency adjustment varies the cavity size and the repeller voltage is the fine frequency adjustment.

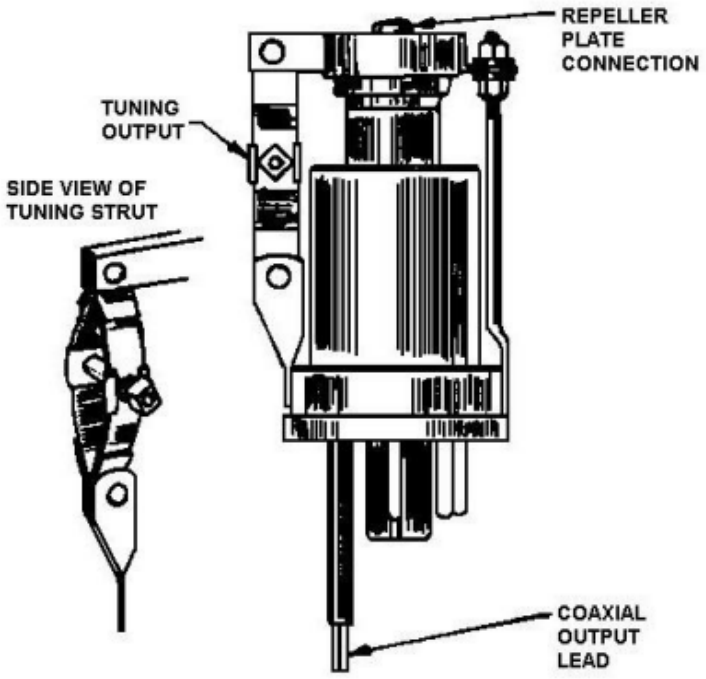


Figure 8. External view of Shepherd-Pierce reflex klystron.

(b) Figure 8 is an external view of a Shepherd-Pierce reflex klystron. The tuning strut is a coarse frequency control that effectively varies the distance between the cavity grids and tunes the resonant cavity by changing its capacitance. The output is taken from the cavity by means of a loop or probe extended through a coaxial lead. The coaxial lead is then coupled to a coaxial line or waveguide, depending upon the type of transmission line used.

d. Magnetron.

(1) General. Practically all radar transmitters which operate above 600 MHz use magnetrons as transmitting tubes. Transit time, which is an upper frequency limitation of conventional tubes, is not a disturbing influence. Although there are some special tube triodes capable of oscillating in the radar frequency range, their output power is too small to be of any use. In addition, the klystron and the Shepherd-Pierce tube operate in the desired frequency range with better power output than the triodes, but are not readily adaptable to pulsed operation.

(2) Description of the magnetron.

(a) General. The most common type of magnetron in use is the cavity magnetron. It has a cylindrical anode that has a series of cavities, a cathode, and a magnet. The magnet is not considered as one of the tube elements but the magnetron will not operate without the magnet. The magnet controls the paths of electrons so that they travel in a path that may be considered circular.

(b) Anode. The common type of magnetron has an anode that is the hole-and-slot type, as shown in figure 9. Figure 9A is a view along the axis of the cylinder which shows only the main outline of the anode. Each cavity is a cylindrical hole joined to the central space by a small slot. Six cavities are shown here but magnetrons often have more or fewer cavities. Figure 9B is a sectional view of the anode showing the cooling fins on the outer surface of the anode, the coupling loop, and the coaxial connection to the coupling loop. The coupling loop takes energy from one of the cavities and transfers this energy to the microwave transmission system which can be a coaxial line or a waveguide. Notice the absence of cavity grids. The electron beam is modulated by the rf field which spreads out from the slot opening, as shown in figure 10. Other types of anodes are shown in figure 11. The choice of anode shape is based on the problems associated with the construction of the magnetron and the desired magnetron operation.

(c) Cathode. The cathode of the cavity magnetron is located along the axis of the anode cylinder. It plays an important dual role in the operation of the magnetron. The cathode is usually indirectly heated and is connected to one side of the heater leads so that only two leads are required for heater and cathode, as shown in figure 12. In addition to being a source of electrons, a magnetron cathode must dissipate a great amount of heat generated by back-bombarding electrons. Many of the emitted electrons return to the cathode and bombard it with a fairly high velocity and give up energy to the cathode. This energy causes the cathode to heat in the same way that the anode of a regular vacuum tube is heated by the energy it absorbs from the electrons that strike it. To compensate for this, the heater current is high during warm-up, but it is drastically reduced while the magnetron is operating. In some high-power magnetrons, the heater current is reduced to zero since the back-bombardment generates enough cathode heating to maintain a normal operating temperature. If the cathode is not properly heated before the high voltage is applied to the magnetron, the magnetron will be seriously damaged. The cathode is considered a part of the resonant system as rf currents are induced on its surface. To prevent electrons from escaping the interaction space, the magnetron has end plates, as shown in figure 12. These end plates should not emit electrons; they are part of a seal so that the interaction space of the magnetron can be evacuated.

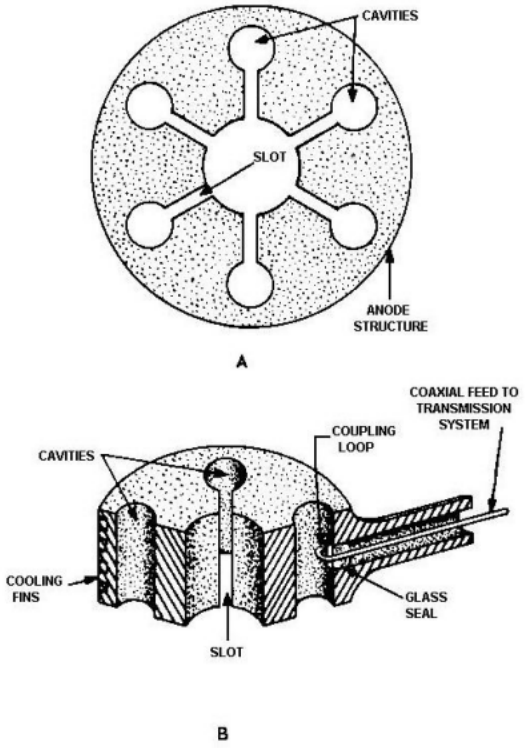


Figure 9. Hole and slot anode.

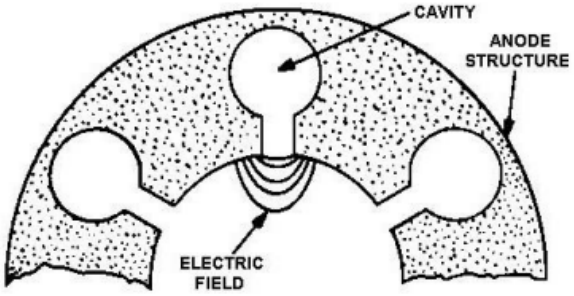


Figure 10. Field at slot openings.

Figure 11. Types of anodes.

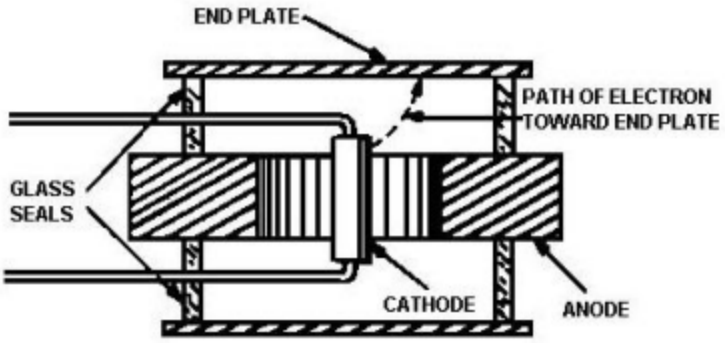


Figure 12. Magnetron cathode and end plates.

(d) Magnet. The magnet used with the magnetron is usually separate from the cathode-anode structure but it is a definite part of the whole magnetron. The magnet is a permanent magnet made of alnico. The flux density of the magnet across the magnetron is critical and should stay at a constant value. Therefore, it is extremely important that a ferrous material is never brought in contact with the magnet at any time because it may change the flux density. The cathode-anode structure of the magnetron is made of copper, so it has no effect on the flux density. The magnet is usually a horseshoe type, as shown in figure 13, and the pole pieces of the magnet are marked north and south. The magnet may be placed around the magnetron in either position but one position may be preferable to the other. If this is the case, the magnetron will be marked and care should be taken to have the magnetic polarity correct. Some magnetrons are supplied with the magnet already attached to the magnetron. These are called packaged magnetrons.

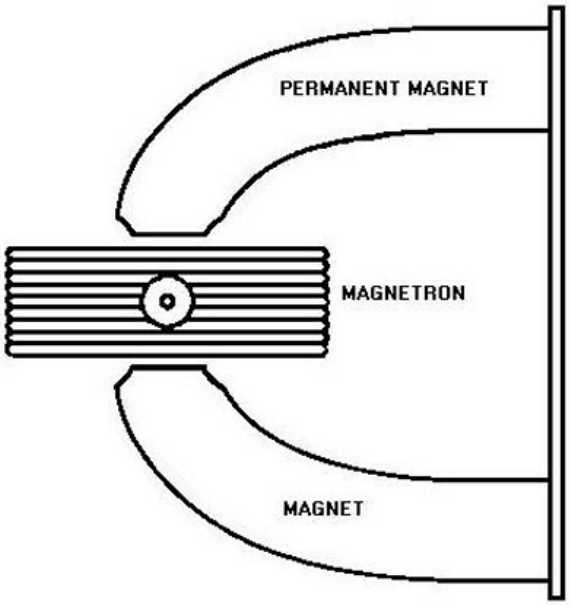


Figure 13. Magnetron and magnet.

(3) Theory of operation.

(a) General. The theory of operation of the magnetron is based on the motion of electrons in combined electric and magnetic fields. The law governing the motion of an electron in an electric field states: The force exerted on an electron in an electric field is proportional to the strength of the electric field. The direction of the force is opposite to that of the electric field. In other words, the electrons tend to move from a low to a high potential and parallel to the electric field. The law governing the motion of an electron in a magnetic field states: The force exerted on an electron by a magnetic field is proportional to the velocity of the electron and the flux density. The direction of the force is perpendicular to both the magnetic field and the path of the electron.

(b) Electron path in a magnetron.

1. Without cavity signal. Aside from the cavities in the wall of the anode structure, the magnetron may be considered as a cylindrical diode with a uniform magnetic field parallel to its axis. In the absence of the magnetic field, the magnetron would behave like a diode. The electrons would travel from the cathode to the anode in a straight line, as shown in figure 14. If a magnet with a weak or moderate magnetic field is placed across the magnetron, the electron path will curve, as shown in figure 15. This is the resultant force of the electric and magnetic fields. In figure 15, A, the magnetic field goes into the page or away from you and causes the electron path to turn clockwise. In figure 15, B, the magnetic field comes out of the page or towards you and causes the electron path to turn counterclockwise. In figure 15, C, the magnetic field is increased slightly and causes the electron path to curve more sharply. When the correct relation exists between the magnetic field strength and the cathode-to-anode voltage, the electron path will develop a series of loops or a cycloidal path, as shown in figure 16, A. This path is symmetrical because there are no cavity signals interrupting the electron path and it is not a true picture of the electron path in an operating magnetron.

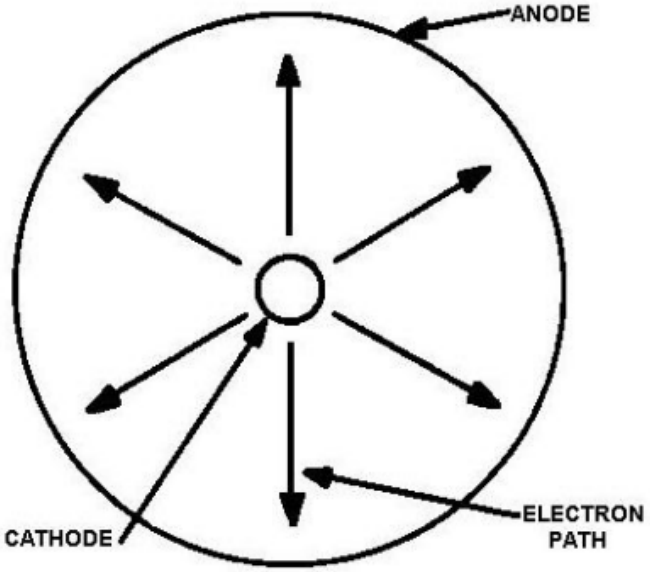


Figure 14. Electron paths without magnetic field.

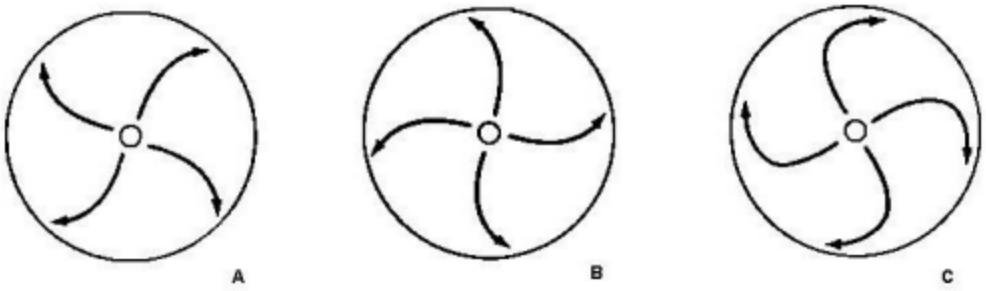


Figure 15. Effect of a moderate magnetic field.

2. With cavity signal. Figure 16, B and C, shows how the electron path is affected when subjected to the velocity-modulating effects of the cavity signals. The electron path spirals outward from the cathode so that the electrons are eventually captured by the anode. An important point to remember is that the electron velocity determines the force exerted on the electron beam by the magnetic field. With a high electron velocity, a greater force is exerted on the electron beam by the magnetic field. F m = 1.6 X 10^{-20} V p B, expresses the force in dynes when V p is the electron velocity in centimeters per second (electron travel perpendicular to the magnetic field) and B is the density of the magnetic field in gausses. When the electrons leave the cathode, they have a high velocity and the force acting on the beam causes them to curve back to the cathode. As the electron beam encounters the RF field across the cavity gap, the electron velocity is slightly decelerated and gives up some energy to that cavity. At the same time, the decrease in electron velocity also causes a decrease in magnetic force acting on it. This allows the electrons attracted by the anode to start a second loop which again may encounter a cavity field and be decelerated. This situation continues until the electrons have decelerated enough for the anode to capture them. Some of the electrons that curve back to the cathode experience acceleration from the cavity fields and continue in their path until they strike the cathode and give up their energy. This is how the back-bombardment keeps the cathode at a high temperature.

(c) Modes. The equivalent circuit of a magnetron is shown in figure 17. There is usually considerable coupling between inductances that are close together, but this does not happen in the magnetron. There is no inductive coupling between adjacent cavities but coupling resulting from radiation of energy from one cavity to the other may occur. When this occurs, the six cavities all being identical resonant circuits closely coupled, three different frequencies are generated. These frequencies differ very little from each other and for each frequency there is one mode of oscillation. If a magnetron is moding (changing modes or frequency while it is operating), the output power decreases considerably. The three modes a six-cavity magnetron may operate in are shown in figure 18. Mode 3 is called the pi (π) mode because the adjacent segments of the anode have a phase difference of 180 degrees or ã radians. This is the most common mode of operation because it requires the least cathode-to-anode voltage and is the most stable mode. In mode 2 the adjacent anode sections have a phase difference of 120 degrees. The frequency of oscillation in this mode is slightly less than mode 3; there is approximately 2 percent change in frequency. If the output impedance or the modulating voltage should change slightly, the magnetron could slip from one mode to the other. In mode 1 the adjacent anode sections have a phase difference of 60 degrees. This mode is rarely encountered because it is difficult to excite. The frequency of oscillation is lower than the other two modes. To prevent the magnetron from moding (changing modes), the segments of the anode are strapped or connected together with a metal ring. The strapping down in figure 19 is for the pi mode, or mode 3. The dots indicate connections of the straps to the alternate anode sections. These straps couple the cavities so that the mode frequency separations are great enough to keep the magnetron from oscillating in another mode. With the magnetron strapped for the pi mode, there is no current flow in the straps because the alternate segments have equal potentials. The other modes, however, have a difference of potential between alternate segments and current flows in the straps. This causes an inductive load in parallel with the cavities which lowers the frequency of oscillation in the undesired mode, increasing the frequency separation of the two modes and decreasing the possibility of moding.

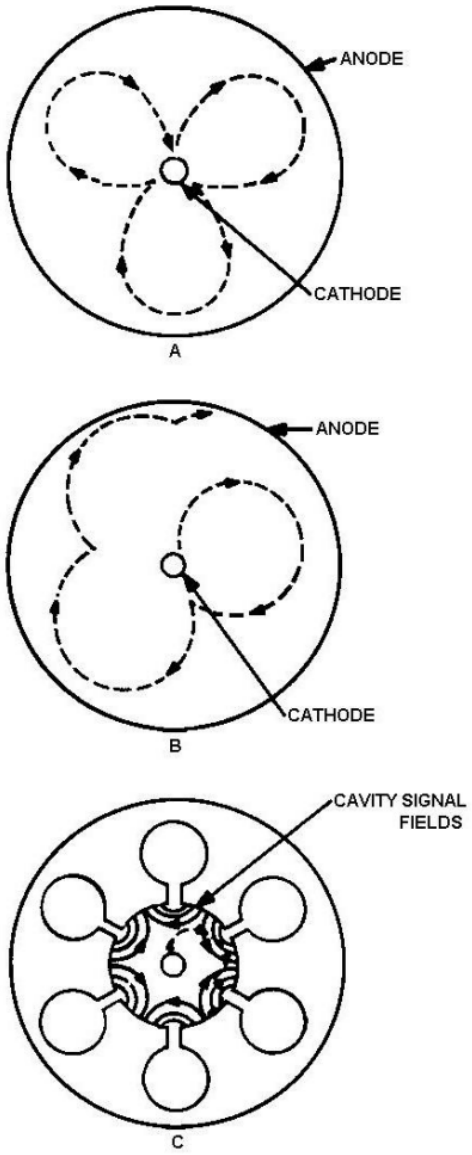


Figure 16. Cycloidal path of electrons.

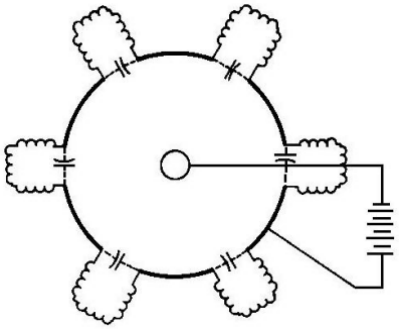


Figure 17. Equivalent circuit of a magnetron.

3. MODULATOR.

a. The modulator controls the shape, duration, and pulse repetition frequency of the r-f energy emitted by the transmitter. The high-voltage pulses formed in the modulator are applied to a pulse transformer, which, in turn, applies them to the magnetron or other transmitter tube.

b. Figure 20 illustrates a typical modulator block diagram of the line-pulsing type. The line-pulsing type modulator is by far the most common type now in use and, therefore, will be the only type discussed. The modulator consists of a pulse-forming network (PFN), which is really an artificial transmission line, and associated charging and discharging circuits. As indicated, the charging path consists of the primary of the pulse transformer, the 0.5-microsecond PFN, and the charging choke.

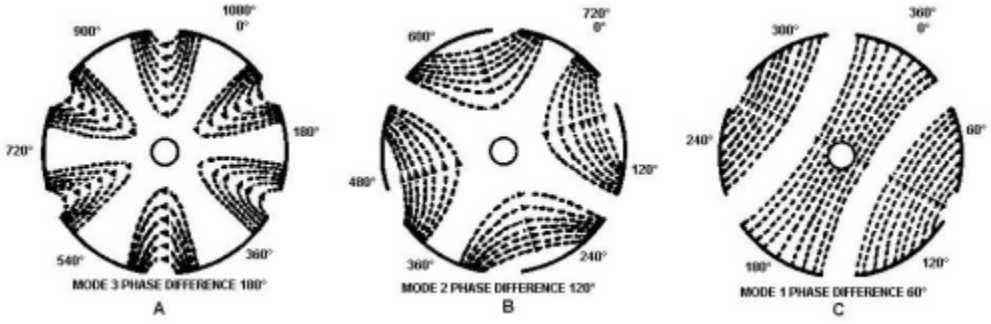


Figure 18. Three magnetron modes.

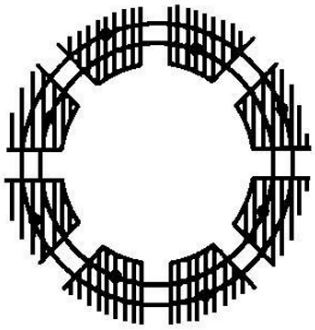


Figure 19. Magnetron strapping.

c. The discharging of the PFN is initiated by the system trigger. The trigger is fed through the cathode follower to the thyratron, causing it to conduct. When the thyratron conducts, a discharge path for the PFN is provided through the primary of the pulse transformer and the thyratron. After the PFN is discharged, the shunt diode bypasses to ground any overshoot of the trailing edge of the pulse. The output pulse is applied across the pulse transformer to the cathode of the transmitter tube, in this case a magnetron oscillator.

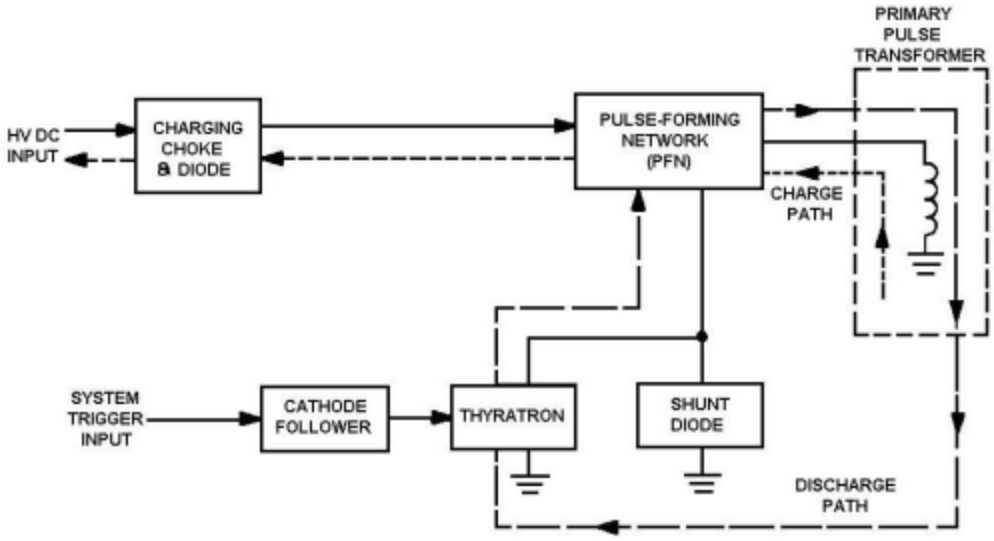


Figure 20. Block diagram, typical modulator.

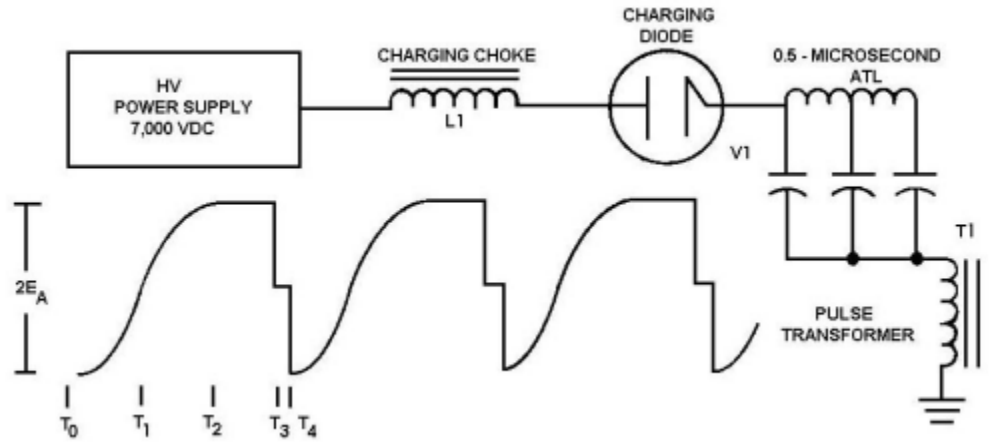


Figure 21. Modulator charging circuit.

d. The modulator just discussed employs a d-c, series resonant charging circuit. This is a common type of configuration in radar modulators. In order to understand the operation of this type of modulator, let's review the development of pulses by pulse-forming networks.

e. A simplified diagram of the modulator circuit is shown in figure 21. As you can see, the main component is an artificial transmission line (ATL). When power is applied to the circuit (T o), current begins to flow. A charge begins to build up around L1. At T1 the ATL has been charged to the applied voltage, and the field about L1 is maximum. At this time the field begins to collapse, cutting the windings of L1 and inducing across the coil a voltage that is series-aiding the applied voltage. This causes current to flow in the same direction, increasing the charge on the ATL so that it becomes greater than the applied voltage. This action continues until the field about L1 is completely collapsed. In a lossless circuit the charge on the ATL would reach twice the applied voltage. In actual practice the charge will reach approximately 1.9 times the applied voltage. When the charge on the ATL reaches a maximum (T 2) the diode will allow it to remain charged to 1.9 times the applied voltage until the thyratron is triggered (T 3) and the ATL is discharged through the primary of the pulse transformer (see fig 20). This applies a pulse nearly rectangular in shape to the magnetron oscillator. The width of the pulse is determined by the characteristics of the ATL. In this example the ATL produces, during discharge, a rectangular pulse having a duration of 0.5 microseconds. It is also assumed that the line is fully charged and that the characteristic impedance of the ATL matches the impedance of the primary of the pulse transformer.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 8

1. What causes conventional oscillators to be inefficient at microwave frequencies?

   A. Interelectrode inductance

   B. Spurious radiation gain

   C. Interelectrode capacitance

   D. Spurious frequency gain

2. What is normally increased to reduce the transit time in microwave tubes?

   A. The plate voltage

   B. The plate current

   C. The plate electrode size

   D. The grid electrode size

3. What primarily determines the reflex klystron oscillation frequency?

   A. The cavity voltage

   B. The cavity current

   C. The distance between cavities

   D. The dimension of cavities

4. What is an advantage of the lighthouse tube?

   A. No tube capacitance

   B. Low radiation loss

   C. Low frequency loss

   D. No tube inductance

5. Which tube is velocity-modulated?

   A. Magnetron

   B. Acorn

   C. Klystron

   D. Lighthouse

6. What is the result when an electron is decelerated by an electric field?

   A. The field gives up energy to the electron

   B. The electron retains its original energy

   C. The electron gives up energy to the field

   D. The field increases the kinetic energy of the electron

7. How are oscillations in a reflex klystron oscillator sustained?

   A. By transferring DC electric field energy to the AC field

   B. By probe excitation inserted in any one of the cavities

   C. By transferring AC electric field energy to the DC field

   D. By probe excitation inserted in any one of the tank circuits

8. What voltage adjustment selects the reflex klystron operation mode?

   A. Cathode

   B. Repeller

   C. Grid

   D. Cavity

9. What adjustment controls the COARSE frequency of the reflex klystron?

   A. Repeller size

   B. Cathode voltage

   C. Grid voltage

   D. Cavity size

10. Which transmitting tube is normally employed at frequencies above 600 megahertzs?

   A. Magnetron

   B. Acorn

   C. Klystron

   D. Lighthouse

11. Which tube is basically a diode?

   A. Magnetron

   B. Thyratron

   C. Strobotron

   D. Klystron

12. What voltage input initiates conduction in a magnetron?

   A. Positive applied to the cathode

   B. Positive applied to the plate

   C. Negative applied to the cathode

   D. Negative applied to the plate

13. What BEST describes the electron path in a magnetron?

A. Circular

B. Cycloidal

C. Elliptical

D. Trapezoidal

14. How does an electron travel in a magnetron?

A. At right angles to the radiation field

B. Parallel to the magnetic field

C. Along a resultant of the magnetic and electric field

D. At right angles to the electric field

15. Why is strapping used in magnetron circuits?

A. To integrate operation mode frequencies

B. To decrease operation mode frequencies

C. To increase operation mode frequencies

D. To separate operation mode frequencies

16. The high-voltage pulse to the transmitter oscillator comes from the

A. modulator.

B. magnetron.

C. duplexer.

D. multivibrator.

17. Which of the following is not affected by the modulator?

A. Pulse shape

B. Pulse duration

C. Pulse repetition frequency

D. Oscillator frequency

18. The thyratron in the modulator functions to

A. amplify the modulator trigger.

B. protect the shunt diode.

C. discharge the PFN.

D. provide a charge path for the PFN.

19. What normally, does NOT affect the magnetron?

A. Transit time

B. Pulse time

C. Resonant cavities

D. Pulse networks

20. Which coupling device is used to couple energy from a magnetron cavity into a waveguide?

A. Transformer

B. Capacitor

C. Loop

D. Delta connection

LESSON 9. SYNCHRO AND SERVO SYSTEMS

MM Subcourse No 0706.....	**Electronics, Part II**
Lesson Objective.....	**To provide you with a general knowledge of the purpose, function, and use of synchro-motors and generators, differential generators, control transformers and resolvers, to include the use of the servomechanism as applied to a basic weapons system.**
Lesson Credit Hours.....	**Three**

TEXT

1. GENERAL.

a. There are many operations in radar and other electronic equipment where it is desirable for two shafts to rotate in synchronization. Because the distance between the shafts is too great, or since one shaft cannot develop enough torque to rotate the other, it is not always feasible for the shafts to be mechanically connected. Therefore, shafts which are designed to rotate in synchronization are generally connected electrically. Systems employing electricity for rotating two shafts in synchronization are called remote indication systems.

b. A remote indication system is designed to produce at one position an indication of an operation at another position, or to transfer information from one position to another. This system may sometimes be called a data transmission system. For example, many radar antennas are designed to rotate through 360-degrees, but are so located that the operator cannot see its position. Therefore, a data transmission system is employed to give the operator the direction in which the antenna is pointing. A pointer attached to a shaft rotates in synchronization with the antenna shaft, and it registers the position of the antenna on a dial at the operator's position. The devices which transmit the position of the antenna to the dial are called synchros. The synchro is a machine that converts mechanical position into electrical position, or electrical position into mechanical position. The entire system, which amplifies and transmits mechanical position by electrical means, is called a servomechanism.

c. Figure 1 shows two synchros which comprise a simple servosystem. Note that one synchro is geared to and driven by the antenna motor and, in turn, that it generates and transmits a rotational force (torque) to another synchro. Therefore, it is called a synchro generator or transmitter. The second synchro is called a synchro motor or receiver, because it receives the rotational force and applies it to the deflection coil. The deflection coil rotates in synchronization with the antenna. Thus, a synchro may be described as an alternating current (AC) machine which is used to transmit angular-position information.

d. There are several trade names for the synchro. One of these is selsyn, a contraction of the words self and synchronous. Originally produced by General Electric, the selsyn is so widely used that it is now synonymous with synchro. Another is the autosyn, as produced by Bendix. Regardless of their names however, all of these units operate alike.

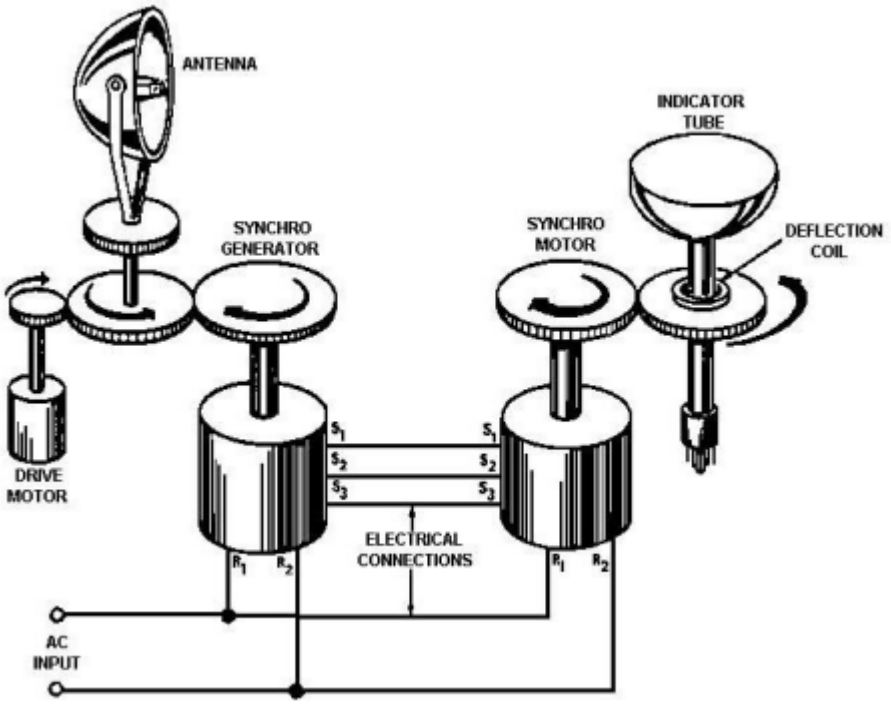


Figure 1. Simple synchro system.

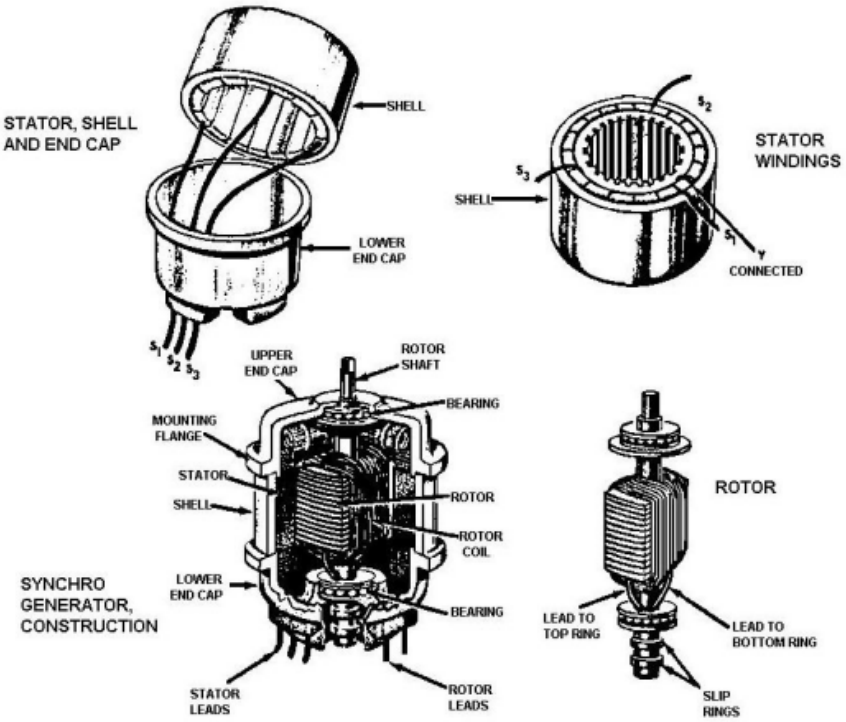


Figure 2. Construction of a synchro generator.

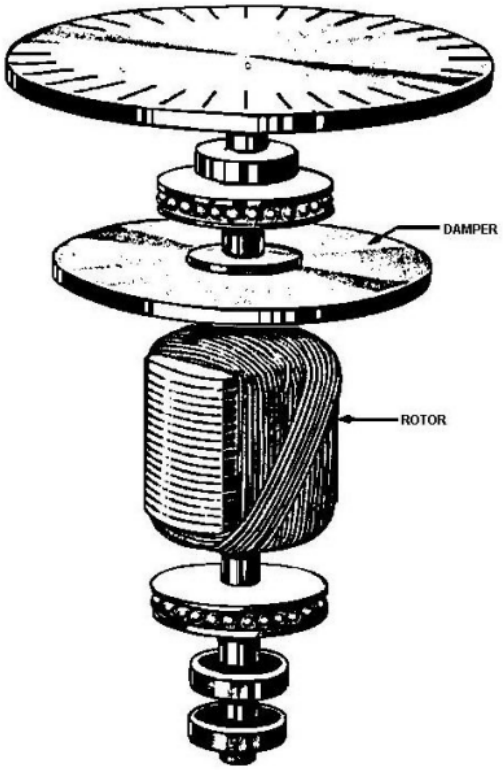


Figure 3. Synchro motor rotor.

2. CONSTRUCTION OF SYNCHROS.

a. Synchro generators and synchro motors are very similar in construction. Therefore, we will discuss the generator and point out the basic differences between it and the synchro motor. The synchro generator, consisting of a stator and rotor, resembles a small AC generator or motor (fig 2). The stator windings are composed of three groups of coils placed at 120-degree intervals around the inside of a laminated iron shell. Note that the three stator leads are brought out through the lower end cap and labeled S 1, S 2, and S 3.

b. The rotor consists of two coils wound on a laminated, soft-iron core and connected in series. The ends of the core are curved so that the air gap formed with the stator is small and uniform. The two leads from the rotor winding are connected to sliprings on the shaft and the entire rotor assembly is mounted on ball bearings to eliminate as much friction as possible. In figure 2, note that the two external rotor leads (R 1 and R 2) are brought out through the lower end cap on the opposite side of the stator leads.

c. The stator of the synchro motor is identical to the stator of the generator; however, the rotor differs in that it has a heavy metal flywheel mounted on one side of the shaft. This flywheel, called an inertia damper (fig 3), serves the purpose of suppressing motor oscillations when the generator it is following suddenly stops or starts. It is mounted so as to turn freely on the shaft for 45 degrees and then turn into a keyed bushing. For slow changes, the flywheel follows along; however, if a sudden shaft change is felt, the flywheel tends to stand still and the friction disk acts as a brake to stop the shaft motion.

3. INDUCTION FROM ROTOR TO STATOR.

a. The operation of synchros is an application of transformer action, with the rotor acting as a primary and each stator winding as a secondary. In figure 4, as the rotor turns to the various positions, different voltages will be induced in each stator winding. Thus, the amount of voltage induced in the stators will indicate the position of the rotor at every instant. To better explain the amount of induced voltage, figure 4 shows the rotor in five different positions. In each case, assume that the polarity of the AC voltage applied to the rotor is such that the magnetic flux will set up N and S poles as illustrated.

(1) In the 0-degree position (A, fig 4), all the rotor flux lines cut the windings of the S 2 coil. The voltage induced in this position is maximum and of such polarity as to oppose the N pole of the rotor (Lenz's law of induction). The voltage from R 1 and R 2 is in phase with the induced voltage from S 2 to common.

(2) In the 60-degree position (B, fig 4), only one-half of the flux lines cut the windings of the S 2 coil. Therefore, the voltage induced in this position is one-half the maximum voltage induced in the 0-degree position; however, the polarity of the voltage is the same as in the 0-degree position.

(3) At the 90-degree position (C, fig 4), the flux lines are parallel to the stator windings and a minimum amount of voltage is induced. Actually, the rotor flux induces equal and opposite voltages on opposite sides of each turn and the net voltage is zero.

(4) In the 120-degree position (D, fig 4), only one-half of the flux lines cut the S 2 stator windings. Just as in the 60-degree position, the voltage induced is one-half the maximum voltage. However, the S pole of the rotor is now closer to the S 2 coil and, therefore, the polarity of the induced voltage will oppose the S pole and be 180 degrees out-of-phase with the voltage in the 60 degree position.

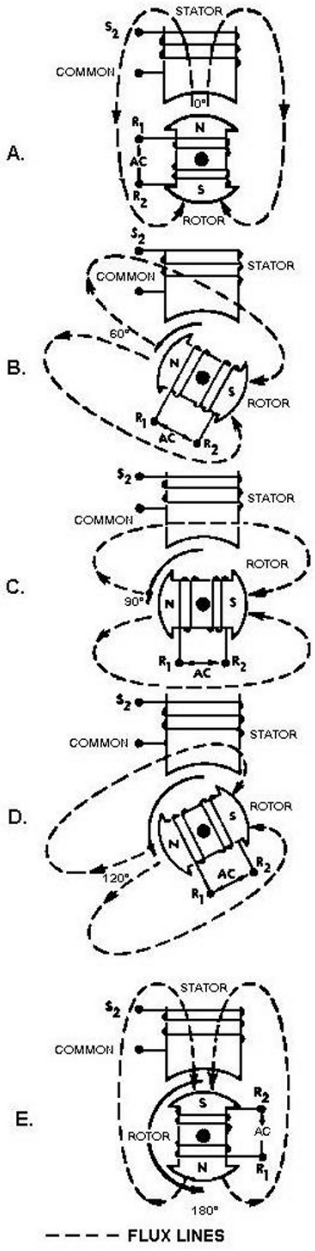


Figure 4. Transformer action in a synchro.

(5) At the 180-degree position (E, fig 4), all of the flux lines cut or link the S 2 stator windings. This induced voltage is 180 degrees out-of-phase with the induced voltage in the 0-degree position and the rotor voltage from R 1 to R 2.

(6) As the rotor continues to turn, the induced voltage decreases from a maximum until it finally becomes zero at the 270 degrees position. The induced voltage then begins to increase until at 360 degrees it is again maximum and in-phase with the voltage of R 1 and R 2.

b. Note that all voltages are either in phase or 180 degrees out of phase with the rotor voltage from R 1 to R 2. Figure 5 illustrates the result of plotting the amplitude of induced voltage against the shaft position. The voltages above the axis are in-phase with the rotor voltage from R 1 to R 2; those below the axis are 180 degrees out-of-phase. Observing the curve, it is evident that the amount and phase of the induced voltage depend upon the position of the rotor. This curve resembles one made by plotting values for the cosine of an angle from 0 degrees to 360 degrees. Therefore, the voltage induced in a stator is proportional to the cosine of an angle made by the rotor shaft and the axis of the stator winding. Expressed as a formula $E_S = k \cos \theta$, where E_S is the voltage induced in a stator winding, θ is the angular displacement between the rotor shaft and the axis of the stator winding, and k is a constant that depends upon the synchro specifications.

4. STATOR TERMINAL VOLTAGES.

a. The electrical zero position is defined as that position in which the rotor coil lines up with the axis of the S 2 stator winding. Figure 6 shows that there are two such possible positions of the rotor. In both the 0 degree and 180 degree positions, the terminal voltage from S 2 to S 3 and from S 2 to S 1 are of the same value, and that between S 1 and S 3 is zero. However, in the 0-degree position, the voltage from S 2 to S 3 (or S 1) is in-phase with the voltage from R 1 to R 2, while the two voltages are 180 degrees out-of-phase in the 180-degree position.

b. The general formula $E_S = k \cos \theta$ is used to determine the amount of voltage induced in a stator winding by a rotor. If the angle é is measured from the electrical zero position, the formula will yield only the voltage induced in the S 2 winding. To obtain the values of the voltages induced in the S 3 and S 1 windings, subtract 120 degrees and 240 degrees from θ. The formulas for the voltages induced in the three windings are:

$E_2 = k \cos \theta$

$E_3 = k \cos(\theta - 120°)$

$E_1 = K \cos(\theta - 240°)$

If a constant, k of S 2, is used and the values of E 2, E 3, and E 1 are plotted through an angular displacement of 360 degrees, the curves shown in figure 7 will emerge. The voltage induced in each stator winding varies continuously from a maximum of 52 volts in one direction, through zero, to a maximum of 52 volts in the opposite direction.

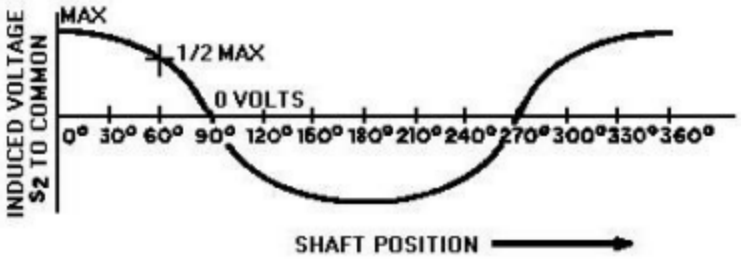


Figure 5. Induced voltage in a stator winding.

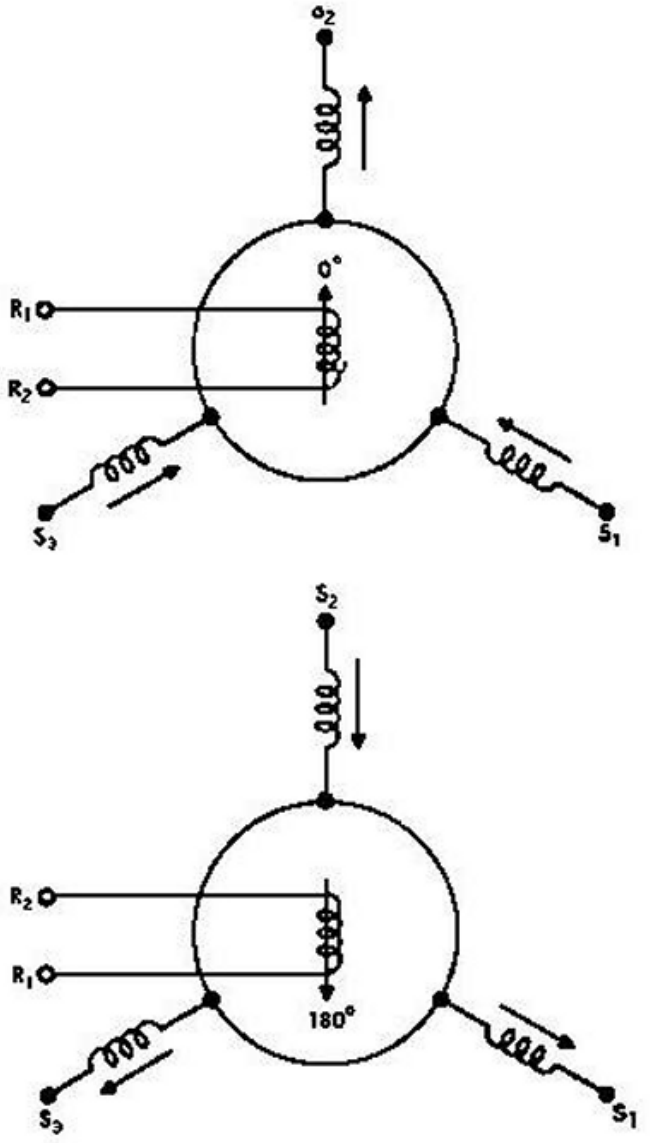


Figure 6. Zero and 180-degree rotor positions.

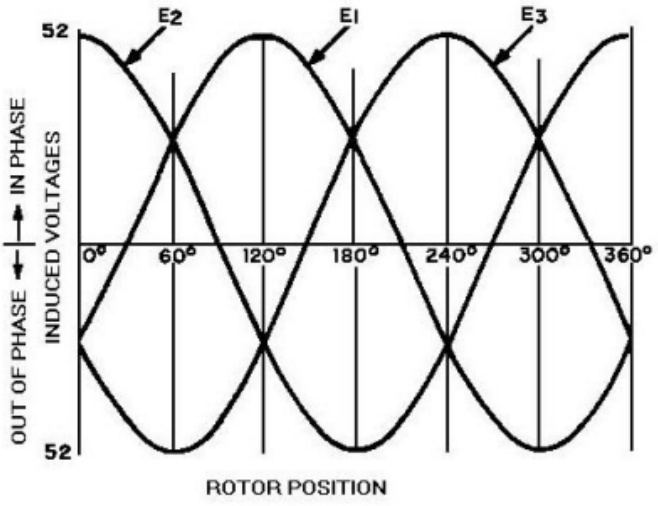


Figure 7. Stator voltage vs. rotor position.

5. OPERATION OF A SYNCHRO SYSTEM.

a. When a generator and motor are properly connected (fig 8) a complete synchro system results, in which the motor shaft follows the generator shaft. Note that the rotors are connected so that both R 1 terminals are joined at one side of the powerline and both R 2 terminals to the other side. Therefore, the two rotors have voltages applied which are identical in magnitude, phase, and frequency. Each motor stator lead is connected to its corresponding generator stator lead; i.e., S 1 is connected to S 1, S 2 to S 2, and S 3 to S 3. Thus, each motor stator winding voltage is opposed by each generator stator winding voltage. If both rotors are in corresponding positions (fig 9), the induced voltage in the two S 1 coils, the two S 2 coils, and the two S 3 coils are equal. Since these equal voltages oppose each other, the voltage between each pair of corresponding stator terminals is zero. Therefore, with this configuration no current flows in the stator windings.

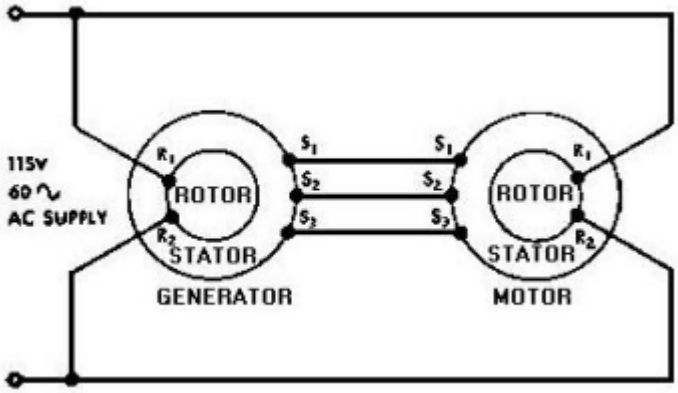


Figure 8. Synchro system connections.

b. If the generator rotor is turned mechanically so that it no longer corresponds to the motor rotor position, the corresponding stator voltages of the motor and generator are no longer equal. In this case, voltage differences will exist between S 1 and S 1, S 2 and S 2, and S 3 and S 3. These voltages cause currents to flow in the stator windings producing flux fields which exert torque on the rotors. Since the generator rotor is mechanically held constant, the motor rotor is turned by this torque until the positions of the rotors again correspond and the stator voltages are equal.

6. TYPICAL STATOR VOLTAGES AND SYNCHRO ACTION.

a. It is easier to understand why the motor rotor follows the generator rotor if we assume two different conditions. First, assume that both rotors are in the electrical zero position (fig 9), and hence, the stator voltages are equal and opposite each other. Therefore, no current flows in any of the stator windings, no torque is produced, and the rotors remain stationary. Second, assume that the generator rotor is turned 30 degrees from electrical zero. This causes the stator voltages of the generator to change, as shown in figure 10, so that a balanced condition no longer exists and current flows in all three stator leads and coils. The amount of voltage induced in each stator is determined by the relative position of the rotor with respect to the stators. When R 1 is positive with respect to R 2, current in each stator lead flows from the coil with the lower potential to the coil with the higher potential as follows:

(1) In the S 1 leads–from common in the motor, down through the S 1 coil, up through the generator S 1 coil, to common.

(2) In the S 2 leads–from common in the generator, up through the S 2 coil, down through the motor S 2 coil, to common.

(3) In the S 3 leads–from common in the generator, down through the S 3 coil, up through the motor S 3 coil, to common.

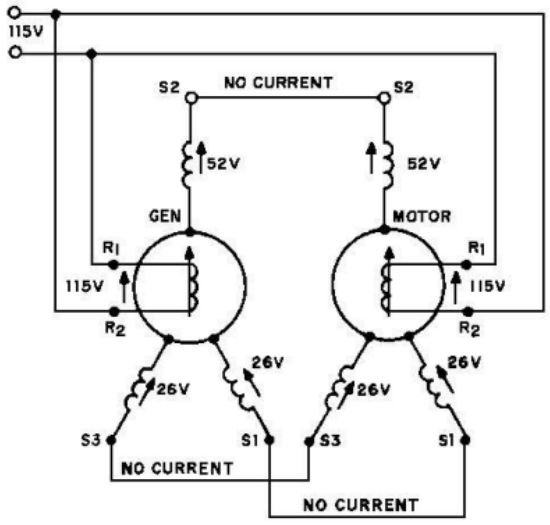


Figure 9. Generator and motor at 0 degrees position.

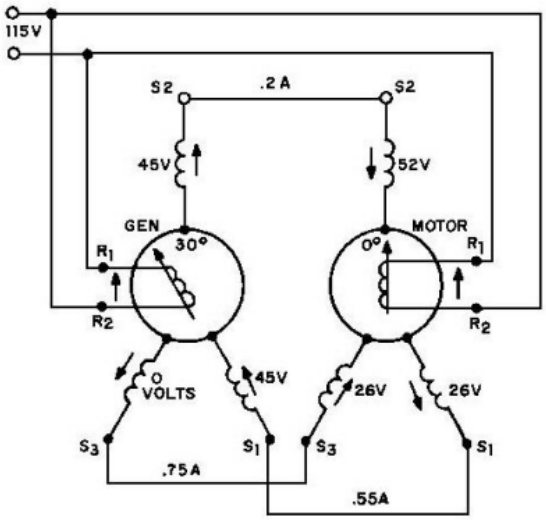


Figure 10. Shafts in different positions.

b. The currents through the stator coils create magnetic fields whose poles are as shown in figure 11. These magnetic poles may be checked by applying the left-hand rule for coils and using the current direction as shown by the arrows. Note that the magnetic poles of the two rotors are identical, while the magnetic poles of the generator stator coils are opposite to those of the motor. Referring to figure 11, it is apparent that the torque exerted is in a clockwise direction for the generator and in a counterclockwise direction for the motor. Either movement would tend to aline the two rotors; however, the generator is mechanically driven and not free to rotate. Therefore, the motor rotor turns in a counterclockwise direction and alines itself with the generator rotor.

7. VARIATION OF TORQUE WITH ANGULAR DISPLACEMENT.

a. The voltages induced in the stator coils, when the position of the generator rotor and motor rotor correspond, are equal and of such polarity as to oppose each other. For this reason, no current flows in the stator windings. However, if the generator rotor is displaced, the balanced condition is upset and currents flow in the stators which produce two opposing torques. Since the generator rotor is the driven element, the motor turns to correct the displacement. As the motor turns and the two shafts approach correspondence, the stator currents become less and less. Finally, at correspondence, the stator currents are zero. The torque exerted on the rotor is almost proportional to the stator currents for small angles; therefore, the torque also becomes less and less as the rotors approach correspondence.

b. The relationship between torque and the angular displacement between rotors is shown in figure 12. It is evident that torque is maximum at a displacement angle of 90 degrees and is very weak at angles close to correspondence. Because of the weak torque near correspondence, synchro motors are usually used for positioning light loads, such as a pointer or a dial.

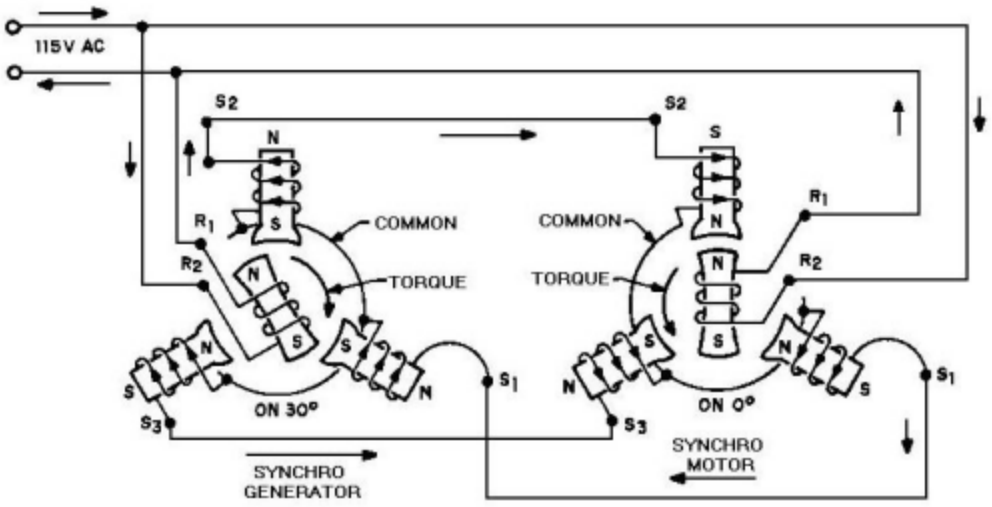


Figure 11. Instantaneous magnetic fluxes created by currents in stator.

c. In spite of the fact that ball bearings are finely machined and carefully selected, friction is always present in the motor even under no-load conditions. To overcome this frictional drag, a compensating torque must be produced. Since torque is produced only when the generator and motor are not in correspondence, the motor must always lag slightly behind the generator. Although a synchro system can never be perfect, it can achieve a high degree of accuracy by reducing friction to a minimum and producing sufficient torque to overcome this friction within a small angle of lag. The smaller this lag and the closer the motor follows the generator motion, the greater the accuracy of the synchro system. A motor accuracy within a half-degree or better is common in synchro systems.

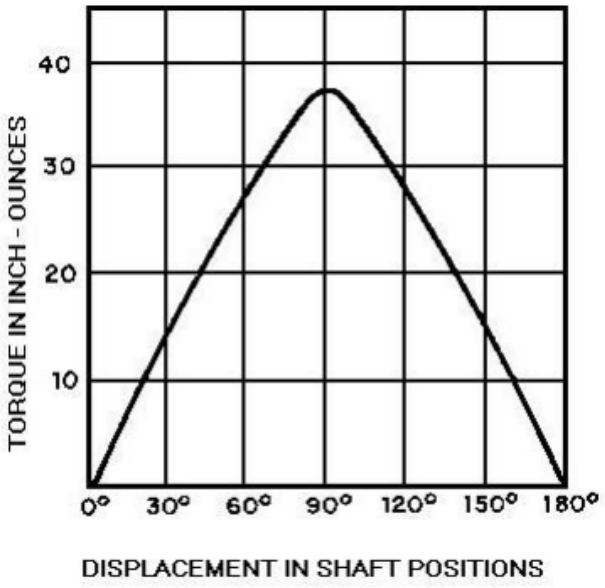


Figure 12. Torque and displacement angle.

8. EFFECT ON SYNCHRO SYSTEM OF IMPROPER CONNECTIONS. A synchro system can be adversely affected if the leads are not properly connected. These connections may have been made purposely to secure a desired effect, or they may have been made accidentally. In the latter case, the recognition of the resulting symptoms may lead the repairman to the discovery of the incorrect connections. Three of the most common connection changes and the results they produce are as follows:

a. R 1 connected to R 2. This results in a 180-degree shift in the motor rotor. The motor then follows the generator, but it remains displaced by 180 degrees.

b. A cyclic shift of stator connections: that is, S 1 to S 2, S 2 to S 3, and S 3 to S 1. This results in a 120-degree counterclockwise shift of the motor. The motor then rotates in synchronization with the generator, but remains separated by 120 degrees. A shift of stator terminals so that S 1 is connected to S 3, S 2 to S 1, and S 3 to S 2 produces a similar effect, but the angle between the generator and motor positions is 240 degrees or 120 degrees clockwise shift of the motor.

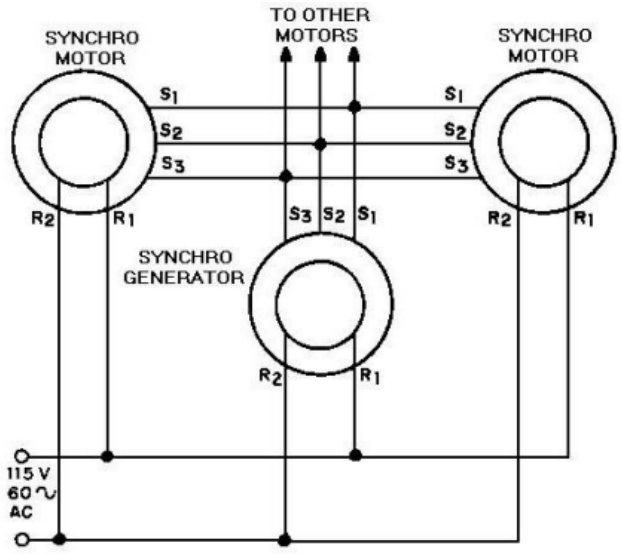


Figure 13. Synchro connections for several motors.

c. Interchanging two stator leads. This causes the motor to rotate in a direction that is opposite to that of the generator. When this is purposely done, the leads interchanged are S 1 and S 3. The position of the motor at any instant is then obtained by subtracting the generator position from 360 degrees.

9. SYSTEM WITH SEVERAL MOTORS.

a. One synchro generator is sometimes used to transmit positioning data to several motors located at different places. The standard type of connection (fig 13) shows that all rotor R 1 leads are connected to one side of the output line and all R 2 leads to the other side of the line. The stator leads are connected in parallel across the generator stator leads.

b. In such a system, a larger generator is required to maintain a high degree of accuracy. If too many motors are connected, output voltages of the generator are reduced and excessive lag occurs in all the motors. Finally, should any one motor turn hard or become jammed, the accuracy of the entire system is affected.

10. THE SYNCHRO DIFFERENTIAL.

a. The differential synchro is a device that is added to a synchro circuit when it is desirable to have the motor position differ from that of the generator by a preset amount. It performs the same function electrically that a mechanical differential performs in a mechanical system. The mechanical differential connects three shafts so that one-shaft turns an amount which is equal to the difference between the amounts that the other two turn. The electrical differential will either add or subtract two inputs and transmit the sum or difference to a motor.

b. As in the ordinary synchros, the differential generator and motor are alike electrically; however, the motor rotor has an inertia damper that damps overdrive and prevents oscillations. The stator of a differential generator or motor is similar to that of an ordinary synchro. It consists of three sets of Y-connected coils wound in slots, which are spaced 120 degrees apart, around the inside of the field structure. The differential rotor, however, is completely different from that of the ordinary synchro. It is cylindrical in shape and has three sets of Y-connected coils wound in slots, which are also spaced 120 degrees apart, around the circumference. The rotor leads (R 1, R 2, and R 3) are connected to the external circuit by three sliprings (fig 14) and brush networks.

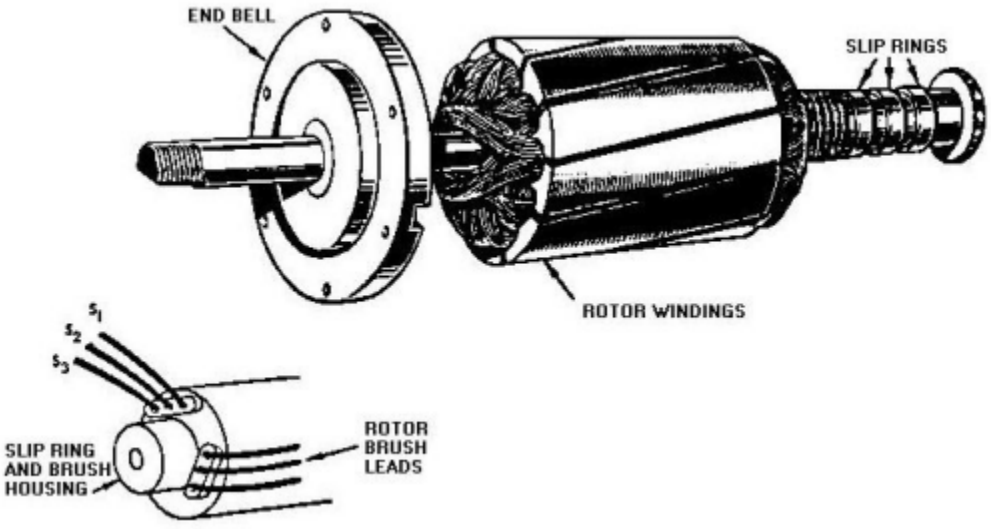


Figure 14. Rotor of synchro differential.

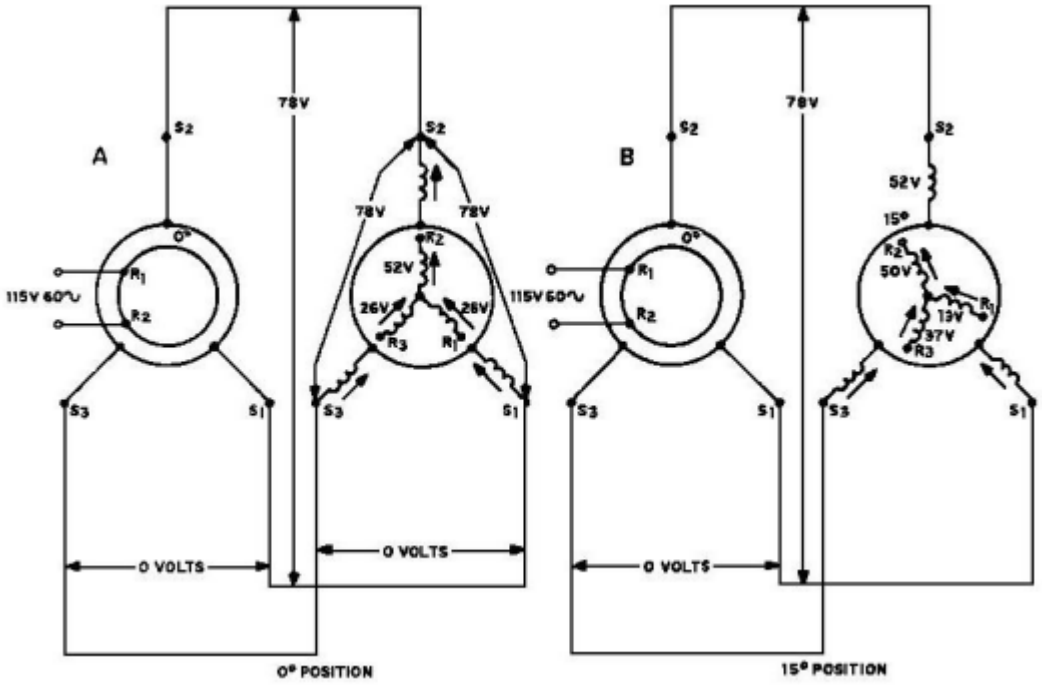


Figure 15. Transformer action in a differential.

c. The synchro differential operates on the transformer principle, much like the ordinary synchro. The stator acts as the primary and the rotor as the secondary of a 1:1 transformer. Because of the airgap, more turns are wound on the stator coils in order to achieve the 1:1 ratio. The 1:1 aspect of this synchro unit is true only when the rotor coils are parallel to the stator coils (electrical zero). Electrical zero is defined as the position assumed by the synchro when the coils connected to R 1 and S 1, to R 2 and S 2, and to R 3 and S 3 are all parallel.

d. Figure 15 shows the transformer action of the synchro differential. Assume that both rotors are in the electrical zero position (A, fig 15), that the stators are connected properly, and that the differential rotor is open. Since the stators are connected together in parallel, the voltages in both sets of stators are equal and in phase. The differential stator voltages, through transformer action, induce similar voltages in each of the rotor windings. If these rotor windings were connected to the stator windings of a synchro motor and power were applied to its rotor, it would aline itself in the electrical zero position. Note that this action is the same as if the differential were not in the circuit.

e. If the differential rotor were turned to the 15-degree position and the synchro generator rotor held in the electrical zero position, the stator voltages would be correspondingly equal as in the 0-degree position. However, the voltages induced in the rotor coils are different because all the flux from each stator winding no longer cuts its corresponding rotor winding. These induced rotor voltages would be as shown in B, figure 15. If the differential rotor windings were connected to the stator windings of a synchro motor (fig 16), the synchro motor would turn to the 345-degree position.

11. CONTROL TRANSFORMER.

a. A control transformer is similar to a synchro motor in that it receives a signal from either a synchro generator or a differential generator. It differs, however, in that its output is a voltage and not a shaft position. It is a variable transformer that transforms an electrical input into an electrical output, an output that may be used to control the position of some device desiring to correspond with the position of the input shaft.

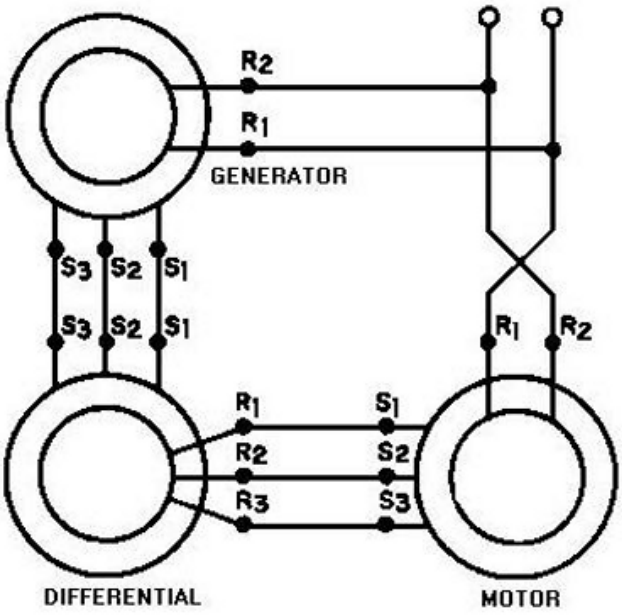


Figure 16. Differential connections.

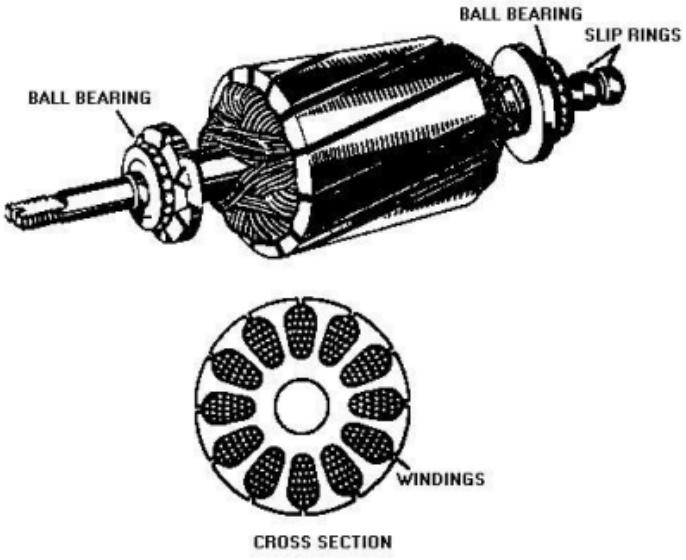


Figure 17. Typical control transformer rotor.

b. Construction of a control transformer.

(1) The control transformer stator is similar to other synchros in that its three windings are Y-connected and spaced 120 degrees apart, but it differs from ordinary synchros in that its windings are composed of more turns of finer wire. Therefore, the control transformer stator impedance is higher and offers more opposition to current flow.

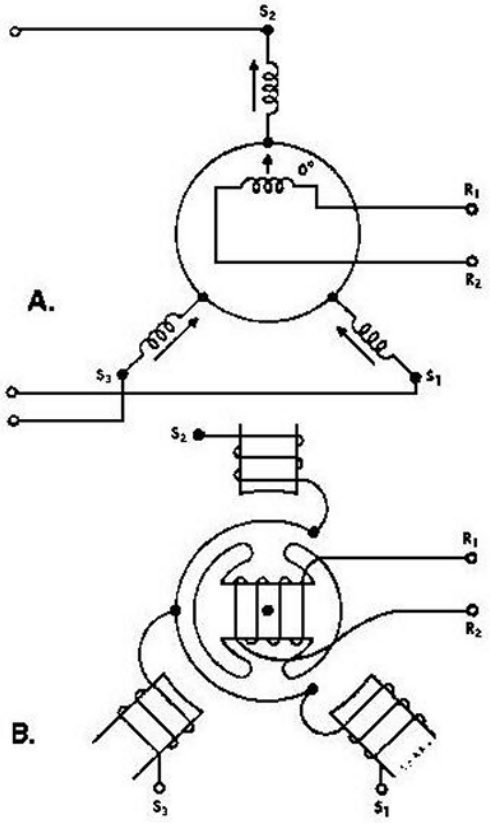


Figure 18. CT schematics.

(2) The control transformer rotor very closely resembles the synchro differential rotor in physical appearance (fig 17). Unlike the ordinary synchro rotor, the control transformer rotor windings are connected in series and have only two external connections through sliprings. Very little current flows in the rotor windings because of the high impedance of the many turns of fine wire.

c. Schematics and electrical zero.

(1) There are two basic types of schematic representations for control transformers (A and B, fig 18). A is used more often than B, although B shows the rotor and stator windings in more detail.

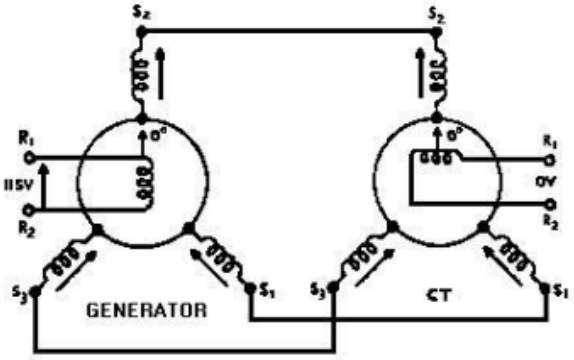


Figure 19. Electrical zero position.

(2) Both A and B represent the electrical zero position. For a control transformer, electrical zero is defined as that position of the rotor in which the stator windings induce no voltage in its windings. This occurs when the rotor axis is perpendicular to the axis of the S 2 winding.

d. Action of a control transformer.

(1) Figure 19 shows a control transformer and a synchro generator connected in the electrical zero position. Since the control transformer rotor is perpendicular to the S 2 coil, no voltage is induced in the rotor. The currents in the S 1 and S 3 coils are equal and opposite and, therefore, induce equal and opposite voltages in the rotor. The net effect is that there is no induced rotor voltage in this position (fig 20).

(2) If the control transformer shaft is turned to the 90 degrees position (fig 19), S 2 will induce maximum voltage in the rotor because they are alined (fig 20). The currents in S 1 and S 3 are equal and in the same direction; hence, they induce voltages in the rotor which are equal and of the same polarity. The net effect is that maximum rotor voltage is induced in this position, which is in phase with the generator rotor voltage.

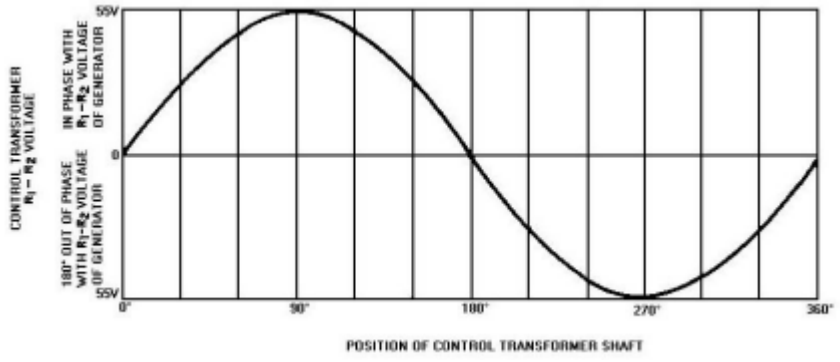


Figure 20. Induced voltage versus shaft position.

(3) When the control transformer shaft is turned to the 180-degree position, the S 2 coil (fig 19) and rotor are again perpendicular. Therefore, the currents in S 1 and S 3 are again equal and opposite, although they are reversed. The net effect is that no rotor voltage is induced in this position (fig 20).

(4) If the control transformer shaft is turned to the 270 degrees position, S 2 is again alined with the rotor. The currents in S 1 and S 3 are again equal and in the same direction. Therefore, maximum rotor voltage is induced in this position, but it is 180 degrees out-of-phase with the generator rotor voltage.

(5) In all intermediate positions of the shaft, the magnitude of the induced rotor voltage varies with the shaft position. The induced voltage is in phase with the generator rotor voltage at shaft positions from 0 degrees to 180 degrees, and 180 degrees out of phase for shaft positions from 180 degrees to 360 degrees. With the generator rotor held in the zero position, this variation is a sine wave (fig 20). The voltages in phase with the generator rotor are above the axis, while those 180 degrees out-of-phase are below the axis.

(6) If the generator rotor is turned from the 0-degree position, the induced voltage in the control transformer rotor approaches zero as the rotor nears the position of the generator rotor. Using the new position as a reference, the induced rotor voltage of the control transformer may also be represented by a sine wave similar to the one in the 0-degree position.

(7) The output voltage, obtained from a control transformer, is called an error signal because the magnitude and phase of this voltage is an indication of how much and in what direction the two rotors are out of correspondence. If the control transformer rotor is turned so that its position corresponds with that of the generator rotor, the error signal will be canceled or nulled. (The position of correspondence is normally referred to as the null point.) If a pointing error exists, this error signal (voltage) will be applied to a device called a servomechanism that will make the necessary correction.

12. SERVOMECHANISMS.

a. In the early days of radar, when sets were simple, automatic means of controlling the antenna position were not available. If an operator wanted to position the antenna on a target and then follow it, another operator, watching the radar indicator, gave him current target azimuth information. As the target moved, the controller had to keep adjusting the antenna position by switching the antenna drive motor on and off. If the antenna were not on target, the indicator would show nothing but "grass" along the trace (time base). This, of course, made tracking quite difficult and unsatisfactory.

b. To improve the effectiveness of radar an automatic method of controlling the drive motor had to be developed. Synchros seemed to be the answer because they could transmit data from one position to another. As long as the motor load was small, the synchro could develop the necessary torque. Otherwise, the required torque was provided by a reversible, variable-speed drive called a servomotor. The complete system, including the error voltage supply circuit, amplifier, servomotor, and the control driver, is currently called an automatic drive control, servomechanism, or servosystem.

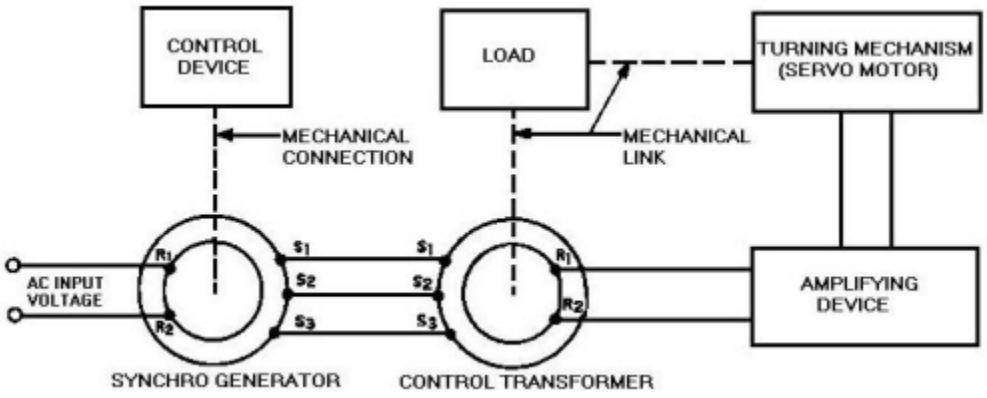


Figure 21. A simple servomechanism.

13. SIMPLE SERVOMECHANISM.

a. A servomechanism, or servo, is a power amplifying system that automatically controls the rotation of an output (motor) shaft in correspondence with the arbitrary motion of a remotely located input (generator) shaft. Figure 21 shows a servomechanism which consists of a synchro generator, a control transformer, an amplifying device, and a servomotor.

b. As the synchro generator rotor is turned by the control shaft to which it is connected, an error voltage is developed across the rotor terminals of the control transformer. The phase and magnitude of the error voltage indicates the direction and amount that the control shaft has turned. The error signal is then amplified and applied to the servomotor. The direction and speed at which the motor turns is determined by the amplified error signal. As the servomotor turns, both the load and the control transformer rotor turn due to the mechanical linkage. As the load approaches the position which corresponds with that of the control shaft, the mechanically connected control transformer rotor is in the position where it nulls the error signal. Therefore, with no error signal, the servomotor stops turning and the positions of the control and load shaft correspond.

MM SUBCOURSE NUMBER 0706, ELECTRONICS, PART II

EXERCISES FOR LESSON 9

1. What is the difference between the rotors of a synchro generator and a synchro motor?

   A. Generator has a gravity damper

   B. Motor has a heavy metal flywheel

   C. Motor has a gravity damper

   D. Generator has a heavy flywheel

2. What is the induced stator voltage formula?

   A. $E_S = k \sin \theta$

   B. $E_S = k \cos \theta$

   C. $E_S = k \tan \theta$

   D. $E_S = k \cot \theta$

3. What indicates the synchro rotor position?

   A. Polarity of the voltage applied to the stators

   B. Polarity of the voltage applied to the rotors

   C. Amount of the voltage applied to the rotor

   D. Amount of the voltage induced in the stators

4. What is the output if the rotor flux lines are parallel to the stator windings?

   A. Minimum stator current and maximum induced voltage

   B. Maximum stator current and minimum induced voltage

   C. Maximum induced voltage

   D. Minimum induced voltage

5. Which connections provide proper operation between a synchro motor and a synchro generator?

   A. S 1 to S 1, S 2 to S 2, S 3 to S 3, R 1 to R 1, and R 2 to R 2

   B. S 2 to S 2, S 1 to, S 3, S 3 to S 1, R 1 to R 1, and R 2 to R 2

   C. S 1 to S 1, S 2 to S 2, S 3 to S 3, R 1 to R 2, and R 2 to R 1

   D. S 2 to S 2, S 1 to S 3, S 3 to S 1, R 1 to R 2, and R 2 to R 1

6. What is the resulting output if the rotors of a generator and motor are in corresponding positions?

   A. Maximum stator current

   B. Minimum stator voltage

   C. Minimum stator current

   D. Maximum stator voltage

7. What determines the amount of induced stator voltage?

   A. Number of magnetic fields

   B. Relative position of the rotors

   C. Number of electric fields

   D. Position of the stator

8. Which angular displacement (in degrees) between rotors produces the greatest torque?

   A. 30 degrees

   B. 45 degrees

   C. 60 degrees

   D. 90 degrees

9. Which displacement (in degrees) results if the generator and motor rotors are reversed (R 1 to R 2)?

   A. 0

   B. 90

   C. 180

   D. 270

10. What happens if the TWO stator leads (S 1 and S 3) are interchanged?

   A. The rotors rotate in opposite directions

   B. A 120-degree cyclic shift

   C. A 180-degree cyclic shift

   D. The rotors rotate in the same direction

11. What is the MAJOR difference between the differential generator and an ordinary synchro?

   A. Rotor

   B. Stator

   C. Brush connection

   D. Slipring connection

12. Which unit generates a voltage output?

   A. Magnetic transformer

   B. Control transformer

   C. Differential motor

   D. Differential generator

13. A control transformer is in the electrical zero position when the

    A. stators induce maximum voltage in the rotors.

    B. rotor axis is parallel to the axis of the S 3 winding.

    C. rotor axis is parallel to the axis of the S 2 winding.

    D. stators induce minimum voltage in the rotors.

14. What information is contained in the output voltage of a control transformer?

    A. Amount and direction of pointing error

    B. Only the direction of pointing error

    C. Only the amount of pointing error

    D. Speed and direction of pointing error

15. What is a MAJOR deficiency of synchros?

    A. The lag error is too large

    B. The lag error is too small

    C. There is not enough torque for heavy loads

    D. There is not enough response for quick changes

16. What determines the direction and speed of a servomotor?

    A. Frequency of the input error signal

    B. Polarity and magnitude of the input error voltage

    C. Frequency of the input excitation signal

    D. Magnitude and polarity of the excitation voltage

17. What is the point called at which rotorshafts of a generator and a control transformer are in correspondence?

A. Rest

B. Null

C. Mechanical zero

D. Electrical zero

18. What happens when the angular displacement is increased between a synchro generator and a synchro motor?

A. Rotor current decreases

B. Rotor current increases

C. Stator current increases

D. Stator current decreases

19. Which is the correct operating relationship between a synchro generator and a synchro motor?

A. The generator leads the motor

B. The generator lags the motor

C. Each moves to correct the displacement

D. Each moves with identical displacement

20. What connections will produce a 120-degree cyclic shift in a synchro system?

A. S 2 to S 3, S 1 to S 1, S 3 to S 2, R 1 to R 1, and R 2 to R 2

B. S 3 to S 1, S 1 to S 3, S 2 to S 2, R 1 to R 1, and R 2 to R 2

C. S 1 to S 1, S 2 to S 2, S 3 to S 3, R 1 to R 2, and R 2 to R 1

D. S 1 to S 3, S 3 to S 2, S 2 to S 1, R 1 to R 1, and R 2 to R 2

SUBCOURSE NUMBER 0706, ELECTRONICS-PART II

APPROVED SOLUTION

LESSON 1.....Frequency Modulation

1.	D	(para 1a)
2.	A	(para 3b)
3.	C	(para 5a)
4.	B	(para 4)
5.	D	(para 8b)
6.	A	(para 7b)
7.	C	(para 7b)
8.	A	(para 5a)
9.	C	(fig 5)
10.	C	(para 8b and fig 5)
11.	B	(para 8d)
12.	D	(para 9a)
13.	D	(para 10a(2))
14.	D	(para 11a(1))
15.	B	(para 5)
16.	A	(para 11a(4))
17.	B	(para 11a(4))
18.	D	(para 11a(7))
19.	A	(para 11a(7))
20.	C	(para 10(b))

LESSON 2.....Limiters and Discriminators

1. B (para 2a)
2. D (para 2d)
3. A (para 2a)
4. B (para 2c)
5. C (para 4b)
6. C (para 4c)
7. A (fig 5)
8. D (para 5b)
9. C (para 5a(2))
10. B (para 9a and 10a)
11. A (para 7)
12. C (para 8f)
13. D (para 8b)
14. B (para 8f and g)
15. B (para 9a)
16. B (para 9a)
17. C (para 8i)
18. D (para 10a and b)
19. C (para 9a)
20. B (para 7)

LESSON 3.....Special Purpose Oscillators

1. C (para 5c)
2. D (para 6b)
3. A (para 6a)
4. D (para 6b)
5. B (para 3a)
6. D (para 5d(2))
7. C (para 7b)
8. C (para 8b)
9. A (para 8c)
10. D (fig 7)
11. B (para 8c)
12. C (para 8c)
13. D (para 5c)
14. B (para 2b)
15. C (para 8c)

LESSON 4.....Multivibrators and Phantastrons

1. D (para 2a(1))
2. C (para 2b(3))
3. A (para 2b)
4. B (para 2c(1), (2))
5. A (para 2c(1))
6. D (para 2b)
7. C (para 3a(1))
8. A (para 3b(1))
9. B (para 3b(2))
10. B (para 3b(3))
11. D (para 4a(1))
12. C (para 4a(2))
13. A (para 4a(3))
14. C (para 4b)
15. A (para 5a)
16. D (para 8b)
17. B (para 8a)
18. B (para 6d)
19. D (para 3a(2))
20. C (para 4b(2))

LESSON 5.....Sweep Generators

1. B (para 2a(4))
2. A (para 2b(1))
3. C (para 2c(2))
4. D (para 2c(1))
5. B (para 2d(1))
6. C (para 2b(1), fig 2)
7. A (para 2c(1))
8. D (para 3b(3))
9. C (para 3c(2))
10. A (para 3b(2))
11. D (fig 7)
12. B (para 3b(2))
13. A (para 4a(1))
14. C (para 4b(2))
15. D (para 4b(3))
16. D (para 4b(2))
17. A (para 4b(4))
18. B (para 3b(1))
19. B (fig 6)
20. B (para 3c(2))

LESSON 6.....Transmission Lines and Waveguides

1.	B	(para 2b(2))
2.	A	(para 3a)
3.	B	(para 2b(3))
4.	C	(para 2a(4)(d))
5.	C	(para3c(3))
6.	C	(para 2)
7.	C	(para 2d)
8.	B	(para 2d(1)
9.	D	(para 2d(3))
10.	C	(para 3f(2))
11.	C	(para 2d(3)(d)3a))
12.	D	(para 2d(3)(d)3b))
13.	A	(para 2d(3)(e))
14.	C	(para 3e(4))
15.	B	(para 2e(2)(d))
16.	D	(para 2e(2)(e)))
17.	D	(para 3m(2))
18.	C	(para 3c)
19.	C	(para 3d)
20.	B	(para 3g(5))
21.	D	(para 3h(3))
22.	A	(para 2d(3)(d)1))
23.	A	(para 3k(2))
24.	B	(para 3m(2)(a))
25.	D	(para 3n(2)(b))

LESSON 7.....Antennas

1.	D	(para 2a)
2.	C	(para 2c(2))
3.	A	(para 9b(1))
4.	C	(para 5e)
5.	D	(para 11b)
6.	B	(para 8a)
7.	B	(para 8b(4))
8.	D	(para 8c(2))
9.	C	(para 9a(3)(a))
10.	A	(para 9b(1) thru (4))
11.	B	(para 10a)
12.	D	(para 10b)
13.	B	(para 11b(1)(c))
14.	C	(para 11b(1)(d))
15.	C	(para 11b(2)(c))
16.	A	(para 11b(3)b))
17.	A	(para 11c(1))
18.	B	(para 11c(3),(4),(5))
19.	D	(para 11)
20.	A	(para 11c(8))

LESSON 8.....High Frequency Oscillators and Pulse Modulators

1. C (para 1a(1))
2. A (para 1d)
3. D (para 2c(6)(a))
4. B (para 2b(1))
5. C (para 2c(2)(a))
6. C (para 2C(4)(b))
7. A (para 2c(4)(c))
8. B (para 2c(5)(b))
9. D (para 2c(6)(a))
10. A (para 2d(1))
11. A (para 2d(2)(a))
12. C (para 2d(2)(c))
13. B (para 2d(3)(b)1)
14. C (para 2d(3))
15. D (para 2d(6)(b))
16. A (para 3a)
17. D (para 3a)
18. C (para 3c)
19. A (para 2d(1))
20. C (para 2d(2)(b))

LESSON 9.....Synchro and Servo Systems

1. B (para 2c)
2. B (para 3b)
3. D (para 3a)
4. D (para 3a(3))
5. A (para 5a)
6. C (para 5a)
7. B (para 6a)
8. D (para 7b)
9. C (para 8a)
10. A (para 8c)
11. A (para 10b)
12. B (para 11a)
13. D (para 11c(2))
14. A (para 11d(7))
15. C (para 12b)
16. B (para 13b)
17. B (para 11d(7))
18. C (para 7a)
19. A (para 7c)
20. D (para 8)